Sea Grant Colleg

ANALYSIS OF MANUFACTURING PROCESSES OF LARGE ANCHOR CHAINS

PHASE II - DEVELOPMENT OF STRATEGIES FOR IMPROVING THE RELIABILITY TO WELDED CHAINS

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ANALYSIS OF MANUFACTURING PROCESSES OF LARGE ANCHOR CHAINS
PHASE II - DEVELOPMENT OF STRATEGIES FOR IMPROVING THE RELIABILITY TO WELDED CHAINS

to

NAVAL SEA SYSTEMS COMMAND
DEPARTMENT OF THE NAVY

by

Robert R. Klimowski
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August 1983

ABSTRACT

The present report contains the results of a study aimed at developing strategies for improving the reliability of flash butt welded anchor chains. The study covered the following tasks:

Task 1: A parametric study of factors affecting the quality of flash welded chains.

Task 2: Development of strategies for in-process sensing and control of flash welding.

Task 3: A study to reduce possibilities of premature failures of welded chain.

The objective of Task 1 was to develop basic understanding of the effects that the major parameters have on flash butt welded joints. These parameters were grouped into two categories, the flashing and upsetting variables, and the effect of each was examined in detail. Results of the investigation are presented in Chapter 2. In addition, a mathematical model for the analysis of heat flow during flash welding was developed. The model is described in Chapter 3, where it is also compared with available experimental data.

Under Task 2, the most recent developments in the area of sensing equipment were first identified. Those findings were then coupled with the results of the Task 1 study, leading to the development of strategies for in-process

sensing and control of the flash welding process.

Finally, under Task 3, potential sources of premature failures of welded chain were identified and their relationships to the basic flash welding parameters were established. To reduce the risk arising from these failures, a number of specific recommendations on appropriate procedures were developed.

ACKNOWLEDGEMENTS

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1. Introduction and Summary

1.1 General background

Large anchor chains used by the U.S. Navy, like the 4-3/4 in. for large aircraft carriers, had traditionally been manufactured by the die-lock forging process, developed at the Boston Naval Shipyard in the late 1920's.(1-4) However, after the closing of this facility, the capability for domestic production of large forged chains ceased to exist in the United States or abroad. This happened despite the fact that Baldt, Inc. of Chester, Pennsylvania had early-on bought the commercial rights for the process; the company never went ahead with the production of the 4-3/4 in. chain because of the high costs associated with retooling (dies) and the limited amount of chain of this size required by the U.S. Navy.(5-7)

An alternative method for fabricating chains, presently employed by several major manufacturers of large anchor chains, is based on the flash butt welding process, which is a variation of electric resistance welding. The heat required for fusion in this process is generated by rapidly recurring short circuits at high electric current. A weld is then produced by the application of a forging force as the workpiece is held by clamping dies (that also conduct the welding current), one mounted on a stationary platen and the other on a movable one. The process commences by bringing the ends of the workpiece in contact, thus initiating a so-called flashing action. The movable platen is continuously advanced to bring new portions of the workpiece into contact. When the right conditions are reached (large enough plastic zone), an upsetting force pushes the pieces together. The rate and duration of the energy input during the process affects weld quality and the size of the heat-affected zone significantly. A low rate results in a deep heat-affected zone, whereas a high rate increases the possibility of inclusion and porosity formations. Weld quality is also a strong function of the upsetting force parameters.

The presently available flash welding technology used for manufacturing large anchor chains is a fairly well automated process with reasonably good reliability. In fact, if stringent quality control measures are adherred to, this process can result in the fabrication of a product with tensile strength properties similar to die-lock forged chains. This is why flash welded anchor chains are currently being used extensively by foreign navies and by commercial fleet and offshore operators in a variety of grades.(7) However, there is currently no facility in the U.S.A. with the capability for producing welded chain in sizes larger than 3-1/2 in.(6) Foreign production facilities exist in a few countries, including Japan and Sweden.

In the mid-70's, faced with the dilemma on whether to reestablish domestic facilities for the production of 4-3/4 in. die-lock forged chains or to proceed with the establishment of capabilities for the manufacturing of the same size reliable flash welded chains, the U.S. Navy sponsored the following studies:

(1) A study made by Battelle Columbus Laboratories in 1977 to examine the quality of welded chains produced by four foreign manufacturers.(8)

(2) A study undertaken by the National Materials Advisory Board (NMAB) in 1979-80 to examine, among other subjects, experiences with die-lock and welded anchor chains, and to recommend further action by the U.S. Navy.(7)

(3) A study initiated in 1981 at M.I.T. aimed at analyzing the manufacturing processes of large anchor chains. Phase I of this study was completed in September 1981.(5) The present report covers the findings from Phase II of the project.

Although no consensus appears to emerge from the studies previously completed, the general feeling one gets from them is that flash butt welded chain should be more carefully and thoroughly investigated to ascertain whether it should ultimately replace, in part or in whole, the die-lock forged ones currently in use. Specifically, efforts should be made in the following areas:

(a) Improvement of the reliability of the flash butt welding process.

(b) Reduction of the possibilities of premature failures of welded chains.

The present research project focuses on these items, as explained in detail in the following subsection.

1.2 Objectives and tasks

The objective of Phase I of this research program was to investigate "pros and cons" of die-lock forged and flash welded anchor chains. It included the following efforts:

(1) Study the state-of-the-art of forged and welded chains.

(2) Study experiences with both forged and welded chains.

(3) Study possible ways for improving the present technology of flash welded chains. One possibility is to improve the reliability of welding by in-process sensing and control in real time.

(4) A limited study of the economic situations with forged and welded chains.

Results of this investigation were published in the final report of the Phase I study.(5)

Phase II of the program, the results of which are described in the present report, is an extension of the third study mentioned above. In particular, its objective is to develop strategies for improving the reliability of welded anchor chains. The study consisted of the following three tasks:

Task 1: A parametric study of factors affecting the quality of flash welded chains.

Task 2: Development of strategies for in-process sensing and control of flash welding.

Task 3: A study to reduce possibilities of premature failures of welded chain.

It should be recognized that a complete development effort to arrive at an actual system that can be implemented by chain manufacturers includes (1) development of basic concepts and strategies, (2) development of complete analytical models and hardware, (3) testing, and (4) implementation in a manufacturing environment. However, such an effort requires a large amount of work and resources. Phase II research focused only on the first item--development of basic concepts and strategies.

Details on the findings for each task are described in Sections 2 through 5 and the Appendices of this report. In the next subsection a summary of the objectives and the findings of each task is given.

1.3 Summary of findings

1.3.1 Factors affecting the quality of flash welded chain

In order to develop methods for in-process sensing and control of the flash welding process, one must first understand the fundamentals of the process. To do this, questions like the following ones have to be answered: Under what conditions can satisfactory welds be made? How should metals be heated? How should plastic upsetting be formed? How can we select optimum combinations of the various parameters involved for joining bar stocks in different sizes and of different materials? What types of defects are likely to occur when each of the various parameters deviates from its optimum value? What are tolerable ranges of these parameters?

The objective of Task 1 of this study is thus to develop basic understanding of the effects that the major parameters have on flash butt welded joints. This task has been successfully completed and its findings are described in detail in Sections 2 and 3 of this report. In what follows, a summary of the approach followed and the findings is given.

Section 2 deals with the factors affecting the quality of flash welded chain. After a brief general description of the flash welding process, the process variables are identified. These are grouped into two categories, the flashing and upsetting variables, corresponding to the two stages of the process. Among the flashing variables, the following ones, considered to be the most important in controlling the temperature distribution at the instance of upset, are considered in detail:

(1) Material consumed during flashing, known as flashing burn-off or just burn-off.
(2) Method and degree of preheat.
(3) Flashing voltage.
(4) Platen flashing pattern.
(5) Initial clamping distance.

The variables considered as important during the upsetting process are:

(1) Upsetting distance.
(2) Upsetting rate.
(3) Upset current.
(4) Flashing voltage cutoff.

Based on extensive literature search, each of these variables is discussed in detail. The discussion includes, among other topics, how each variable affects the quality of the flash weld as well as how the variables are interrelated. Whenever possible, the discussion is quantitative. It was found, however, that in certain cases very little quantitative information is available in the literature, so that only qualitative trends could be safely established.

Following the discussion on the process variables, relationships of possible weld defects to these welding parameters are established. Both metallurgical and mechanical defects are considered. The first category includes flat spots, voids, oxides, cracking, bar stock microstructural defects, and die burns. Under mechanical defects, the misalignment of the link ends prior to upsetting and the case of non-uniform upsetting are included. Section 2 ends by providing some guidelines with respect to acceptable ranges of the process variables analyzed.

The subject of heat flow during flashbutt welding anchor chains is treated in Section 3. After analyzing the physical phenomena that take place during the preheating, flashing, and upsetting stages of the welding process, a simple mathematical model is proposed, based on the work by Savage et al.(10) The model is a one-dimensional one, assuming that there is no temperature gradient in the thickness direction of the pieces to be welded together. A modification of the moving planar heat source solution is used in the analysis. Both constant velocity and constant acceleration platen movement patterns are modelled.

Results obtained using the developed heat transfer model and how they compare with existing experimental data are described in the latter part of Section 3. The best agreement with experimental data was achieved in the case of linear flashing. However, it appears that the model has too many simplifications to adequately represent the temperature distribution when parabolic flashing (constant platen acceleration) is used.

1.3.2 Strategies for in-process sensing and control of flash welding

Although many automatic welding machines for various processes have been developed and used, today most of them, except for very few recent models, are what can be called "preprogrammed" machines. In these, optimum welding conditions have been determined in advance either through experiments or based on previous experience, and these conditions are then set into the machine. Then, once a welding operation is started, it is performed by following the predetermined program. No adaptive control systems which can adjust the welding conditions during the process to take care of possible external disturbances thus exist in these machines. As a result, the reliability of the preprogrammed automatic welding machines are limited to certain values, say 90%, 95%, or 99% depending upon the machine being used and the conditions of the joint being welded.

During the last few years there has been a tremendous surge in interest, both in industry and research institutions, to improve the reliability of welding by in-process sensing and control, on the basis of recent developments in modern electronics technology. Having this in mind, as well as the desire to produce reliable flash welded anchor chains, the objective of Task 2 of this research effort is to develop basic strategies for improving the reliability of flash welding by in-process sensing and control. Section 4 of this report describes the results of the study. A summary of the findings is discussed below.

Given the fact that sensing is one of the most critical aspects of an adaptive control system, the initial efforts of Task 2 were directed towards identifying the most recent developments in the area of sensing equipment. In particular, and having in mind what variables should be sensed during the flash welding production of anchor chains, the following types of sensors were investigated:

(1) Optical transducers, including optic fibers, lasers, and video equipment.

(2) Optical image processing methods.

(3) Acoustic sensors, both active and passive, and including those based on ultrasonics.

(4) Combinations of ultrasonics and linear arrays.

(5) Tactile transducers.

The pros and cons of these sensors with respect to the flash welding process were investigated in some detail. On the basis of the results of this investigation, conceptual designs of adaptive control systems for the flash butt welding of anchor chains were developed. During the development special care was taken in ensuring that the systems were compatible with the findings of Section 2. Note that several of the ideas applied to the conceptual design were borrowed from other similar processes.

The proposed system, shown in detail in Figure 4.15, consists of the following:

(1) Measurement of bar stock geometry prior to preheating.

(2) In-process sensing of bar stock's temperature during preheating.

(3) In-process sensing of the bending operation through optical sensors.

(4) In-process sensing and control of the flash welding operation; parameters that may be included in this system are the flashing voltage, the flashing current, the burn-off rate, the platen movement pattern, the upset current and force, and the voltage cutoff.

(5) Examination of the flash welded link using optical sensors.

(6) NDT, real-time examination of the welded link.

(7) NDT and visual examination during and after the stud insertion (and welding) process.

It should be of course understood that the proposed system is more than likely redundant. In other words, it may be possible to abolish several of the proposed sensing requirements.

However, to arrive at such decisions more research and development efforts are required.

1.3.3 Methods to reduce possibilities of premature failures of welded chain

Experience with welded anchor chains indicate that premature failures occur not only in the flash welded joints but also in regions other than it. For example, fractures often initiate from notches created by arc welding the stud to the main body of the chain.

The objective of Task 3 is to identify potential sources of premature failures of welded chain and to suggest methodologies for their elimination. In what follows the major findings of this investigation are briefly discussed. For a more detailed description one is referred to Section 5 and Appendix B.

The first thing one should note when trying to investigate the subject of premature failures of welded chain is the lack of a large number of well documented and publicly available case studies. Despite this shortcoming, it was possible to compile a list of some of the most common causes of chain failure, on the basis of these scant reports and of a basic understanding of the phenomena involved, as follows:

(1) Brittle fracture.

(2) Failures induced by the stud insertion process.

(3) Failures initiated by defects caused by improper gripping electrodes during flash welding.

(4) Lack of fusion in the weld zone.

(5) Heat Affected Zone (HAZ) microcracking.

(6) Fatigue.

(7) Lack of maintenance, wear, and abuse.

(8) Corrosion.

All these causes have been analyzed in detail. Wherever possible, case studies available in the open literature are cited (see Appendix B). Based on this analysis, a priority listing on how these causes influence the anchor chain's failure rate was developed. It is believed that lack of fusion, hot cracking, and electrode/grip defects constitute the primary causes, followed by corrosion, brittle failure, and stud-induced failures. The last category includes wear, abuse, and fatigue.

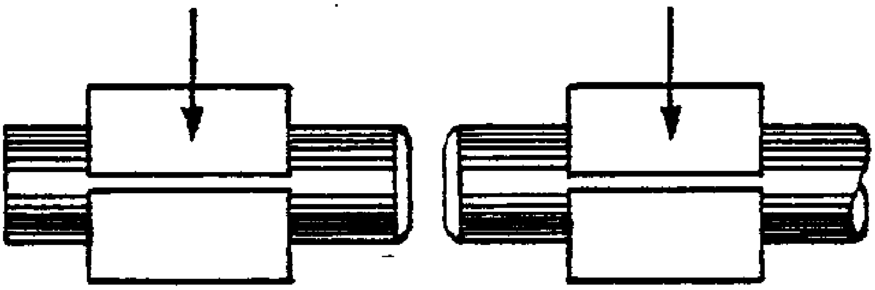
To reduce the risk arising from these failures, a number of procedures are recommended. They are broadly classified under three headings: maintenance, in-service inspection, and modification of materials and machinery used in mooring systems. For each of these areas specific recommendations on appropriate procedures are offered.

2. Factors Affecting Flash Welded Chain

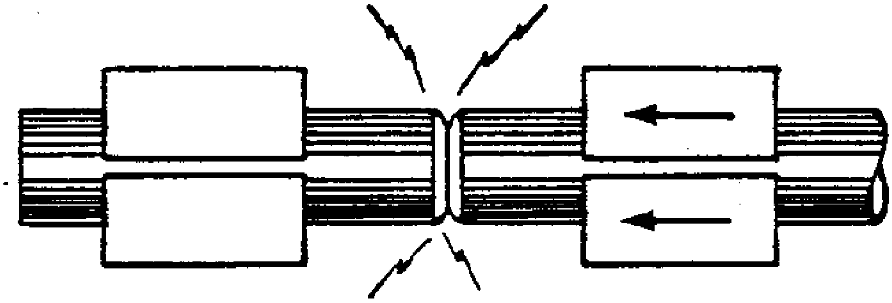
2.1 Flash welding process description

Flash welding is a type of resistance welding process which is used to produce a butt joint between two parts of similar cross section. The joint is achieved by producing a coalescence simultaneously across the entire joint area of the abutting surfaces, and then applying an upsetting force to bring the parts into complete contact. This applied force causes the molten metal, formed at the surfaces, to be expelled and the base metal to be upset. The combination of melting and upsetting yields a uniformly welded, solid joint which required no filler metal.

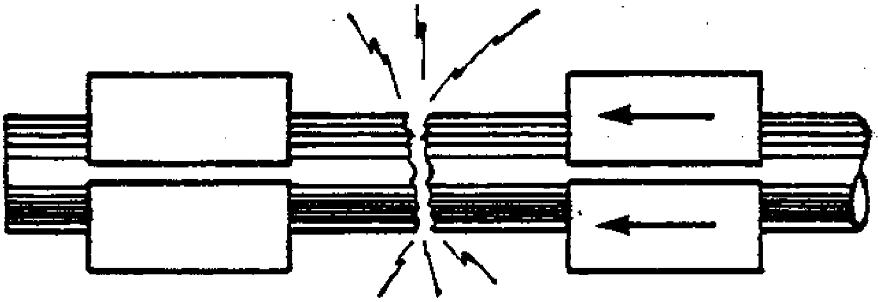
The heat required for the coalescence of the base metal is usually achieved through resistance heating of the contacting surfaces. The workpieces are usually gripped, and held firmly, in electrical contacts which are connected to the secondary of a resistance welding transformer. As these grips begin to move toward each other, a voltage is applied to the workpiece. Once the movement of the workpiece has begun, the small irregularities of the abutting surfaces begin to make contact and large amounts of heat are generated at these "bridges" because of their resistance to the flow of electric current. (See Figure 2.1 for sequence.) The amount of heating is a function of the applied voltage and the contact area of the material. As the current increases,



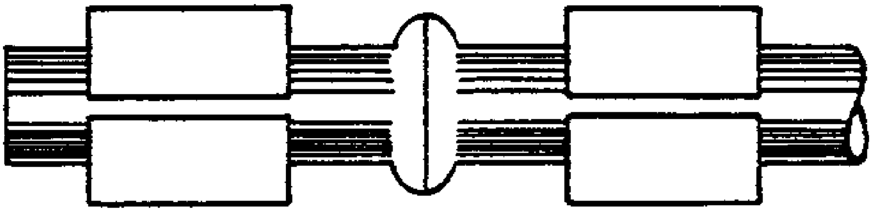
I. POSITIONING AND CLAMPING OF PARTS



2. APPLICATION OF FLASHING VOLTAGE AND START OF PLATEN MOTION



3. FLASHING PHASE



4. UPSET ACTION AND CURRENT TERMINATION

FIGURE 2.1 Flash welding sequence (11)

so does the metal's melting rate. If this rate is allowed to increase, some of the molten metal is violently expelled from the surface at the points of contact. Some additional heating is also achieved from the arcing which occurs across the gap between surfaces, and this combined action is known as flashing.

This heating process continues until the entire mating surfaces have reached the melting temperature of the metal, Tm, so that the workpiece can be forged into the appropriate chain link shape. When this predetermined temperature is reached (usually about Tm), an upsetting force is applied and the chain link is fabricated. In the cases of dealing with large workpieces, the required resistance heating to bring the metal surface temperature to its melting point may prove to be prohibitive or, at least, uneconomical. Usually these larger cross-sections are preheated to expedite the welding process and to lower the welding machine's current-drawing requirements, (see Figure 2.2 for a typical welding current history). This is the case with large anchor chain where the bar stock os preheated sufficiently to allow the flashing and upsetting action to be performed by a relatively small machine. The preheat is accomplished by placing the chain bar stock in a gas or electric furnace and uniformly heating it to the desired temperature. In the case of some anchor chain production, the bar stock is preheated to temperatures of around 1550°F. This additional heating

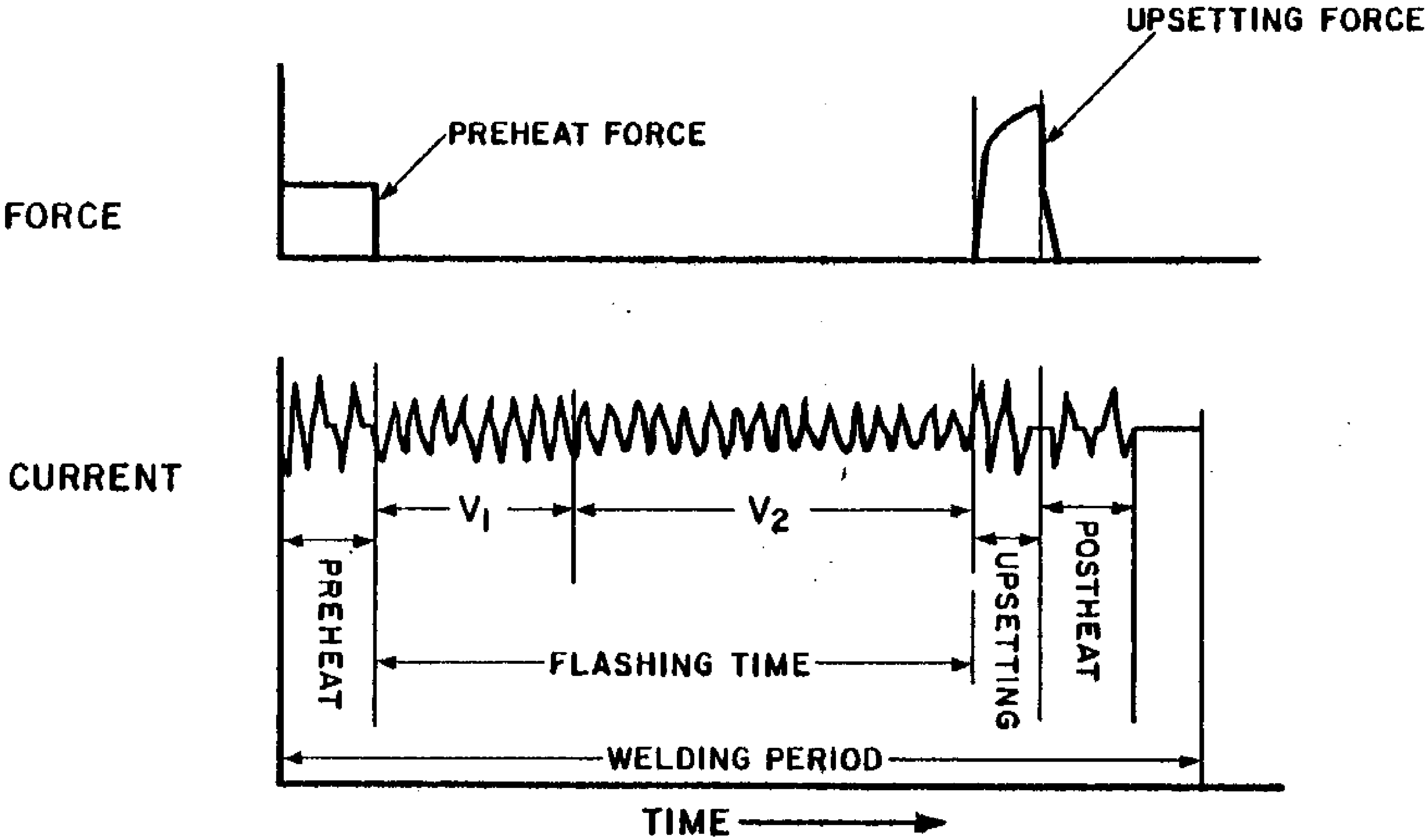


FIGURE 2.2 Flash welding time, force, and current variables(11)

is required, especially in the production of chain link, because of the joint being formed is between the ends of the same piece of stock. Because of the nature of the workpiece (Figure 2.3a) there is more inherent resistance to the upsetting force than is normally found in other flash welding production welds such as window frames or even train rails (Figure 2.3b). A typical sequence for fabricating anchor link chain is depicted in Figure 2.4.

2.2 Identification of process variables

In order to be able to select an optimum flash welding condition it is necessary to not only identify the variables present in the process, but also to establish the inter-relationships that exist among these variables. This knowledge will give the individual the ability to understand the impact that a small change in one variable will have on the others as well as on the overall process. For easier study, the flash-butt welding variables will be divided into two groupings. The first of these to be examined will be the flashing variables, followed by a study of the upsetting variables.

2.2.1 Flashing variables.

According to Savage,(9) the flashing variables control the temperature distribution which exists at the instant of upset. Of all the flashing variables present, the following are considered to be the most important during the welding operationL

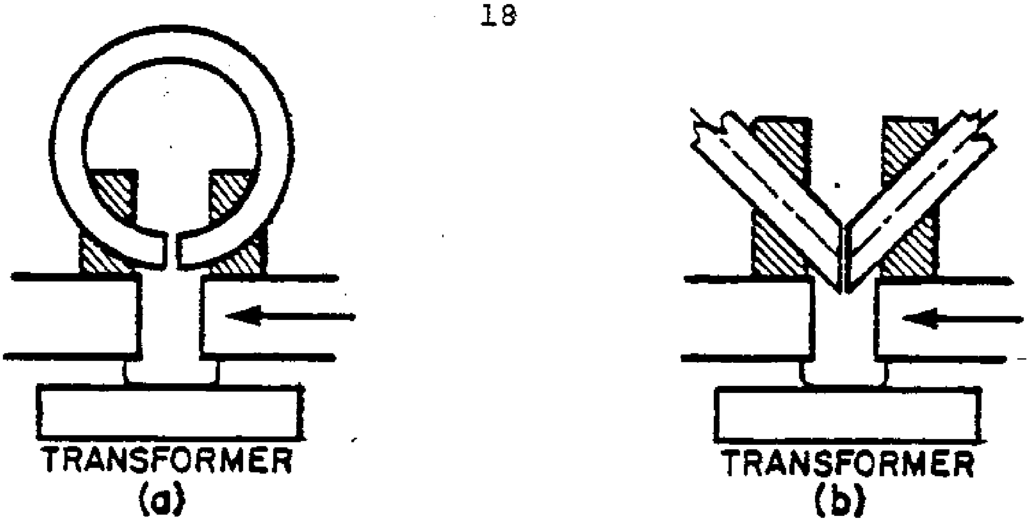


FIGURE 2.3 Types of flash welds(12)

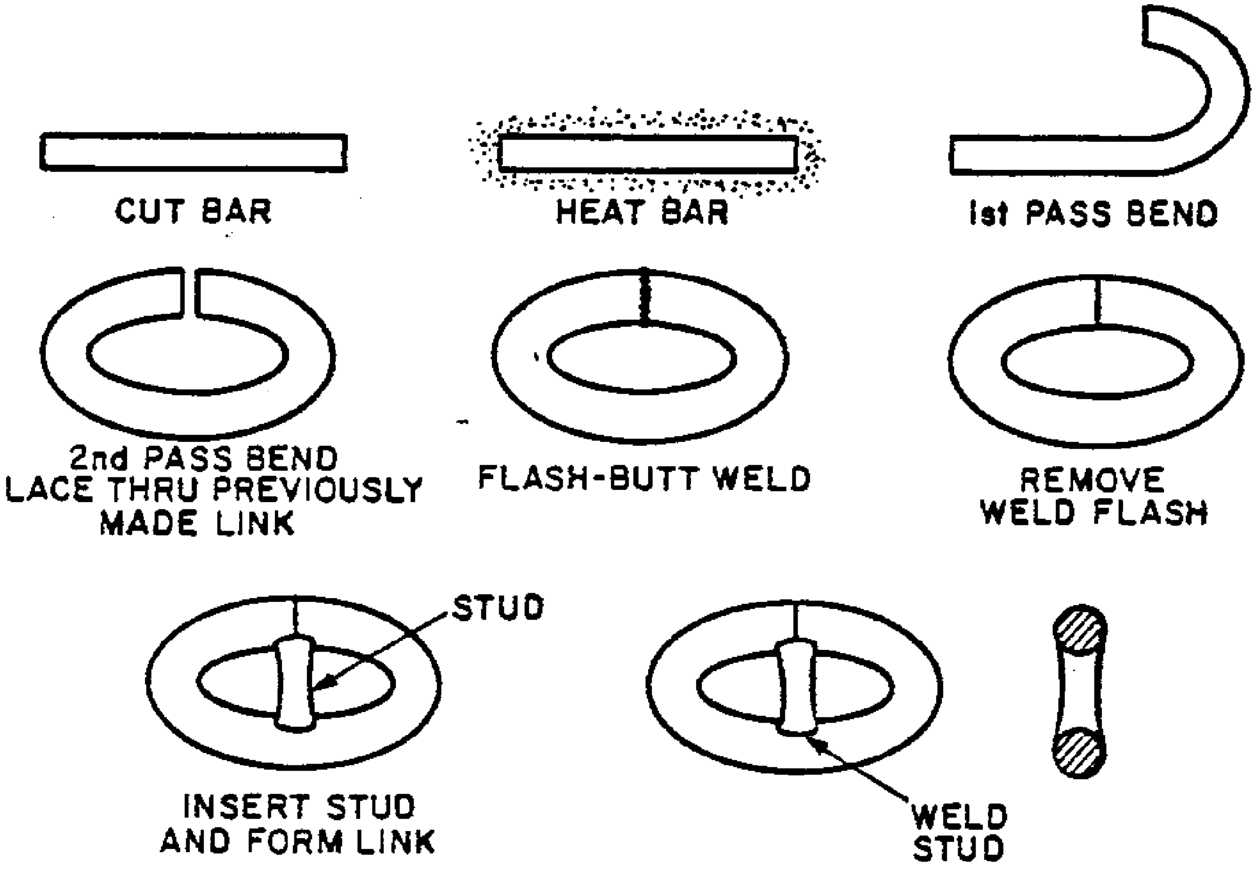


FIGURE 2.4 Anchor link forming process

1) Material consumed during flashing
2) Method and degree of preheat
3) Flashing voltage
4) Platen displacement with respect to time
5) The initial distance set between the clamping dies at the beginning of the weld cycle

Over the years, the relationships among these variables have been studied by welding engineers, scientists and through shop production experience. Because of this research, and other on-going studies, it is possible to satisfactorily predict the temperature distribution that will be present in a workpiece just prior to the upsetting action. To make this prediction, certain input properties are required, such as the physical dimensions, flashing variables and material properties, all of which can be readily obtained from the machine settings and physical measurements.

Since there is an inter-dependence among many of these variables, it is possible to obtain similar temperature distributions with different combinations of the flashing variables. The objective is to find the best combination which gives a favorable temperature distribution, good end weld quality, requires a relatively short flashing time, and is economical. Finding this optimum combination can be difficult because in an effort to meet one criterion other qualities may be negatively affected. A good example of this "conflict" would be the economical aspect which is in direct opposition to the high quality weld requirements. Trade-offs must be made in these situations to ensure that optimum conditions and product are reached.

A. Material consumed during flashing

Within the flash welding community, this quantity of material is known as "burn-off" or "flashing burn-off".(9) Because this material is lost during the flashing operation, it is highly desirable from an economical standpoint to keep this value at a minimum. When the flashing begins, the average temperature of the interface quickly rises and approaches the material's melting point. Once this temperature is reached, a dynamic thermal equilibrium exists between heat dissipation and input. This condition gives rise to a stable temperature distribution over a wide range of burn-off. The minimum burn-off is that which is required to achieve this stable temperature distribution on the abutting surfaces of the chain link. Very rarely is this actual minimum value used since there is danger of not fully attaining the desired temperature profile. In most operations a conservative approach is followed, and a slightly larger burn-off is used since the benefits achieved through a small economic trade-off have a great effect on weld quality. The amount of burn-off required can be roughly calculated(10) and it has been shown that this parameter appears to be only a function of the workpiece's thermal diffusivity and of the welding machine's platen flashing pattern.

From laboratory experiments and actual welding practice, very little evidence has been found to indicate a direct relationship between the workpiece's dimensions and the amount of burn-off required to obtain a desired temperature profile. The physical dimensions do influence, however, the amount of time required to achieve this profile, the amount of preheat required, and also the size of the upsetting force required to produce intimate contact of the link ends. Within the chain industry, the amount of burn-off is important since it controls the final length of the link and can also cause various residual stresses within the links due to slight changes in its dimensions. If the burn-off changes from link to link during chain manufacturing, the accumulative effect of the residual stresses can be quite complex. These residual stresses can be detrimental to the chain quality and could lead to premature failure of the link. Fortunately, the chain industry deals with symmetrical stock material and uniform temperature profiles and proper burn-off's can be fairly easily achieved. Much more difficulty arises in flash welding of large dimensional stock that has a varried cross-section such as a railroad rail. In these cases, special grips are required to afford the proper heat sinks to the thinner areas of the rail so that a uniform temperature can be achieved throughout the end surfaces.

Here many times even the conservative burn-off values aren't used, but are further increased in an effort to ensure weld quality.

B. Method and degree of preheat

There are several different manners through the workpiece can be preheated, depending on the type of welding facility that is available and also based on the physical dimensions of the part being welded. One of the most commonly used methods of preheating is accomplished by bringing the parts together under light pressure and then energizing the welding transformer to start resistance heating. The large current flowing through the metal between the dies causes Joule (I^2R) heating throughout the workpiece. The temperature distribution across the joint during preheating approximates a sinusoidal waveform with the peak temperature point at the interface.(11) Since the clamping dies also act as heat sinks, besides supplying the electricity to the workpiece, the temperature of the workpiece drops off away from the interface until it reaches approximately the temperature of the dies at the clamping point. This preheating is quite different from the very localized resistance heating which occurs during flashing at the small bridge contacts and which results in localized melting and metal expulsion. In this type of preheat the light contact pressure is maintained until a predetermined surface temperature is achieved, and then the flashing sequence is started.

A second method of preheating is available for pieces that can be totally heated within a furnace, whereby the entire workpiece is brought uniformly up to the desired temperature. This is the case with anchor chain links since during the manufacturing process the chain is produced by inter-weaving the new bar stock through the last completed link. Once the new link is "laced" through the previously completed link, it is bent in a die press to form a more closed link (see Figure 2.4). This new shape allows for the flashing and upsetting action that follows, and since the temperature of the workpiece is still quite high, the flashing can be carried on quite easily. The higher temperature of the metal also allows for the upsetting motion to be accomplished by a much smaller force than would be required for a cooler workpiece. This method does have the disadvantage of having to handle "hot" workpieces, a fact that causes some higher wear rates on the grips and dies. The main reason for preheating anchor chain stock in this manner is to facilitate the bending operations which must be performed during the link formation. In the cases of large size stock material, it may also be of an advantage to use this preheat method since it would avoid the requirement of using a very large rated current welding machine to preheat the workpiece by resistance heating.

As a summary of the preheating sequences it should be noted that certain distinct advantages are achieved by the use of preheat in flash welding operations. The following are a few of these advantages:

1) With the use of preheat, a temperature distribution with a flatter gradient is produced. This distribution is present throughout the flashing operation and it allows for the distribution of the upset over a longer length of the workpiece. Because of the preheating, the upset distribution is more uniform than is found in the cases where no preheat was used.

2) As discussed earlier, the use of preheat can extend the capacity of the flash welding machine by allowing larger cross-sections to be joined that could not be achieved without the preheat. The capacity of the machine could also be expanded not only in physical dimensions of work-pieces, but also in the types of material it can handle. With sufficient preheat some higher strength metals may be joined which would normally be beyond the machine's capability.

3) The use of preheat makes it easier to start and sustain flashing with a lower secondary voltage. This is accomplished by the fact that the preheat raises the temperature of the abutting surfaces and requires less electrical input to

bring the metal to metal contacts to their melting and flashing point.

Along with these advantages there seems to be some disadvantages. Here the emphasis will be placed only on those affecting the chain manufacturing process. Most preheating is accomplished through "manual" methods, and the degree to which this is an advantage rests directly on the care the operator takes during the process. The overall process relies heavily on the individual's skills and how well the operator can reproduce the same preheat from link to link. In many cases, bar stock is preheated until it "looks right" to the operator. This approach does not give consistency to the end product, and it will definitely allow a variation in the product quality to exist from shift to shift and plant to plant. For these reasons, some manufacturers choose not to use a preheating process during flash welding operations.

C. Flashing voltage

The flashing voltage plays an important role in the flash welding operation, and during most procedures, this value falls in the range of 2 to 16 volts.(12) For each particular welding task the voltage should be selected in such a manner that it is the lowest possible setting which still allows a good flashing action. The selection of the lowest flashing voltage is aimed at minimizing the number and depth of surface irregularities that are formed during flashing. As the flashing voltage increases, the size of the "craters" formed in the abutting surfaces increases due to the more rapid melting action and metal expulsion.(13) From this a generalization can be formed that the larger the area of the contact bridge at the time of metal expulsion and the higher the current, the larger the crater that will form in the joining surfaces. This relatively large crater formation can be detrimental to the weld strength because, even after upsetting takes place, some of the normally flashed material may remain locked in these holes. Even if foreign material is not forced into these openings, the upsetting action may prove insufficient to "fill" them all with molten metal and hence yield a weld that has porosities and possible stress concentrations.

Once the flashing voltage is selected, it is input into the welding machine by the welding transformer tap setting. This minimal voltage required for the task at hand is sufficiently low so that arcing does not occur across the faces of the material to be joined. As the process continues, and small contacts are made between metal protuberances from the opposing surfaces, a secondary current begins to flow which causes heating in these bridges. The current increases rapidly and the metal quickly reaches its melting point with an accompanying violent expulsion of the molten metal caused by the induced magnetic field. With this action the secondary current begins to decay in accordance with the electrical characteristics of the secondary. This overall process is best described by Figure 2.5, which schematically represents the voltage and current waveforms during flashing. As can be seen from the figure, there is sufficient voltage induced by the secondary to overcome the gap between the interfaces such that at the instant at which the bridge is broken the current can momentarily arc over. This arcing causes some additional heating and then the cycle starts again with new bridges being formed.

D. Platen flashing pattern

Another very important variable in the flash welding process is the flashing pattern established by the motion of the platen during the welding operation. As the platen advances part of the workpiece towards the stationary face, a graph of the time-displacement relationship can be produced. This graph is known as the flashing pattern and is of great value in determining the burn-off and temperature distribution.(11) From analysis and experimentation it has been shown by Nippes and others(10) that under appropriate conditions, a stable temperature distribution is achieved when the average temperature of the flashing interface reaches the melting temperature of the material. Once these conditions are met, little benefit is obtained by further flashing. The best flashing pattern is the one which

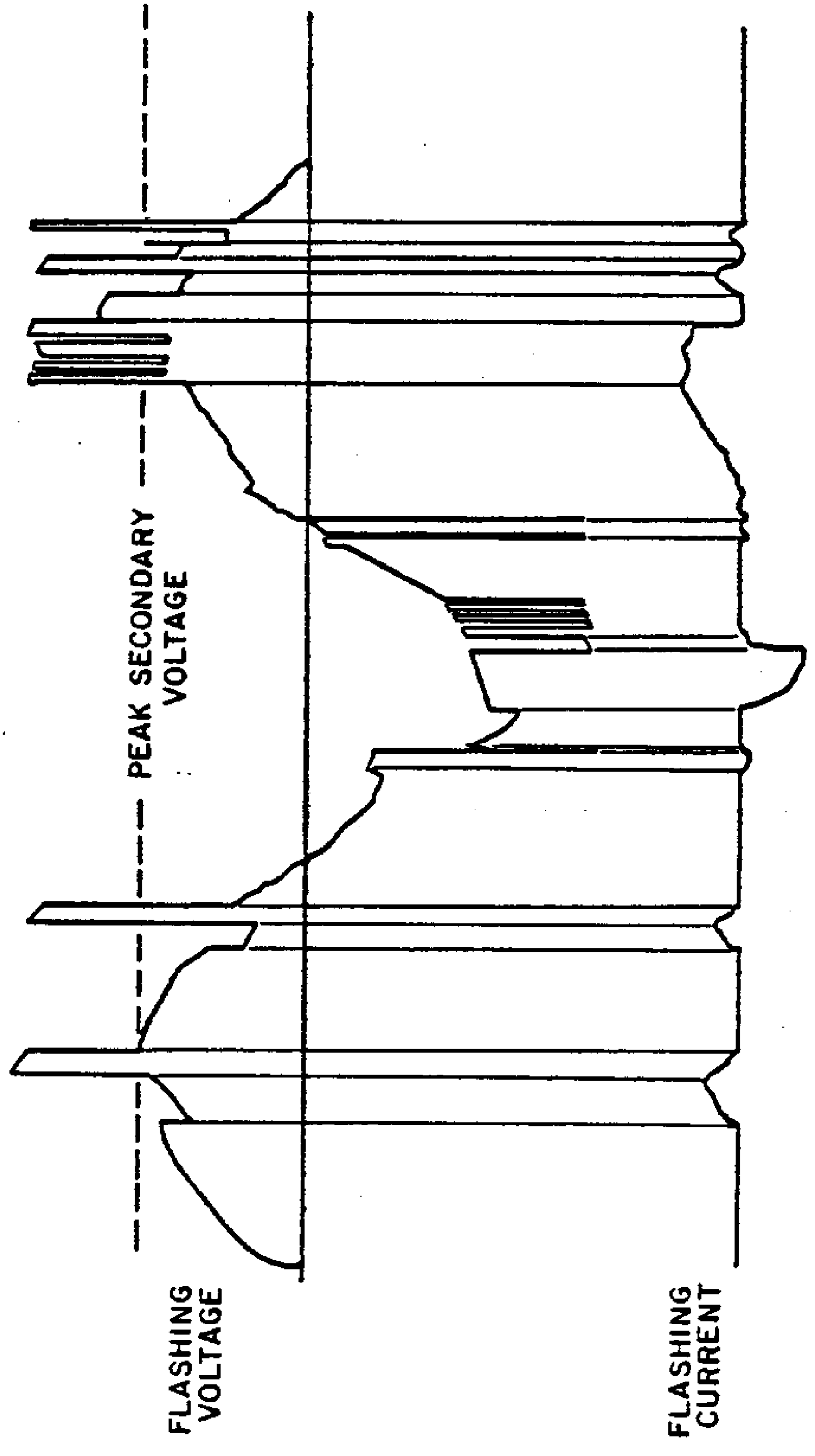


FIGURE 2.5 Voltage and current waveforms during flashing(9)

provides the desired stable temperature distribution with the least burn-off.

Several types of platen motion can be achieved, but through experience it has been shown that in most cases the flashing pattern should have an initial period of constant velocity (linear) motion of the one part toward the other, to facilitate the start of flashing. Once the flashing has been initiated, this constant velocity motion should be changed into an accelerating motion. This accelerated motion is known as "parabolic flashing" and is characterized by the constant rate of acceleration of the platen. As the acceleration increases, so does the steepness of the stable temperature gradient. From this it can be seen that the shape of the temperature distribution is controlled by the flashing pattern and hence, the behavior of the metal during up-setting is also controlled. It can be seen that weld strength and integrity are very much dependent upon the choice of the flashing pattern. If the wrong pattern is chosen for a certain welding task, the result could easily be an inferior joint as well as poor product. This cannot be tolerated in anchor chain production because of the critical nature of the product, and hence, this flashing variable should be very closely controlled.

E. Initial clamping distance

According to Savage (9), the temperature distribution is also influenced by the length of the heat flow path between the flashing interface and the water-cooled clamping dies. In general, the initial clamping distance and, to a more limited extent, the physical dimensions of the workpiece determine the length of the heat flow path. Under normal circumstances, as the clamping distance increases, the temperature gradient becomes more gradual. There are some limitations to this generality in that the thermal diffusivity of the particular material will create a limiting length of heat-flow path beyond which no further effect is noted. Thermal diffusivity is defined as:

$$\alpha \equiv \frac{\kappa}{\rho \; c}$$

where ρ is the density (lb/in^3)

c is the specific heat ($Btu/lb\ {}^{o}F$)

κ is the thermal conductivity ($Btu/hr\ ft\ {}^{o}F$)

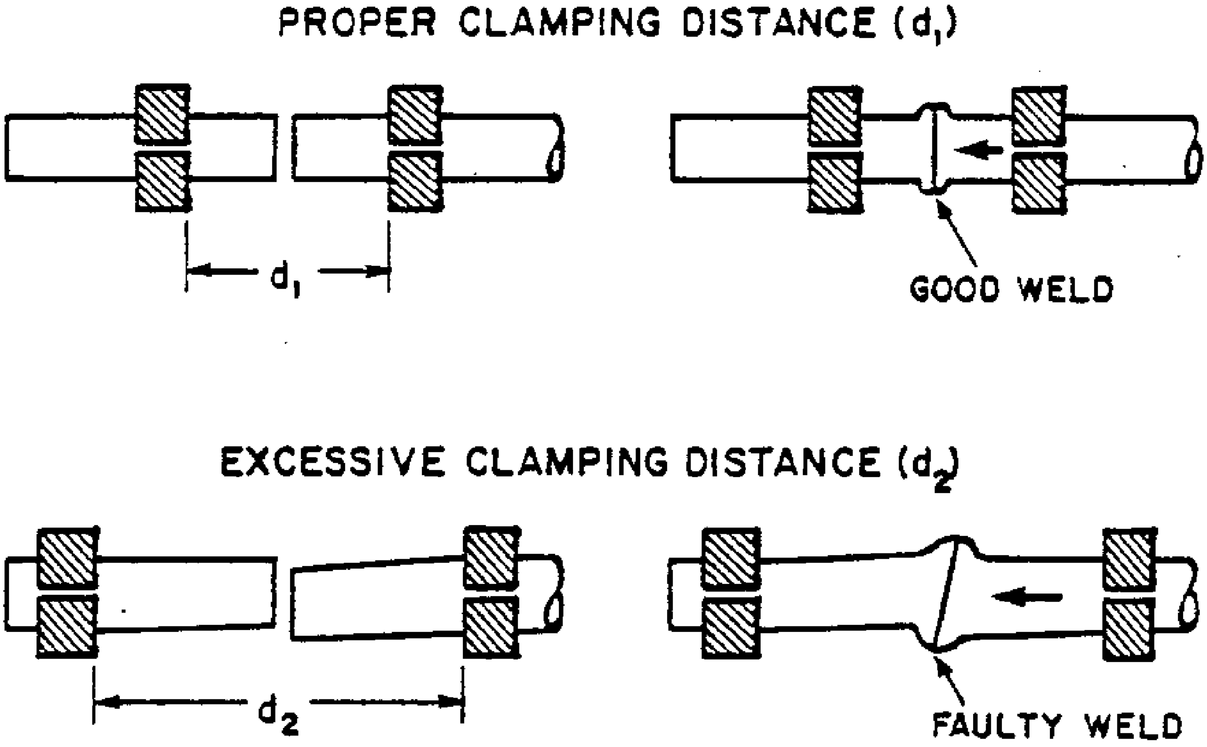
The critical clamping length is known as the "effective-infinite-clamping distance" and to extend clamping beyond this distance will yield no benefits to the temperature distribution or the quality of the weld.

As the thermal diffusivity of the stock material increases, the welding sensitivity to clamping distance also increases. Since, in the case of anchor chain material the thermal diffusivity value (approximate equal to .01 in^2/s) is relatively small, the clamping distance is not very large. This is fortunate in that, due to the nature of the physical dimensions of the link and the cross sectional size, any large clamping distance requirement would create a major problem in the chain production process. The short clamping distance also decreases weld alignment problems that would be caused by a long section of bar stock being subjected to a large upsetting force (see Figure 2.6). As a matter of comparison, the thermal diffusivity of aluminum (i.e., flash welded window frames, etc.) is approximately .09 in^2/s and requires a long clamping distance while α for anchor chain steel is around .01 in^2/s and requires a clamping distance of only a few inches.

Besides the five major flashing variables already discussed, there are numerous other variables that may be considered part of the flashing process. These points are also important but they are usually considered as being included in the major variables or as part of the machine design through good engineering practice. The following is a non-all inclusive list of other variables that need to be considered during design:

1) Size of the electrodes supplying voltage to the clamping dies, to ensure that no localized burning occurs.

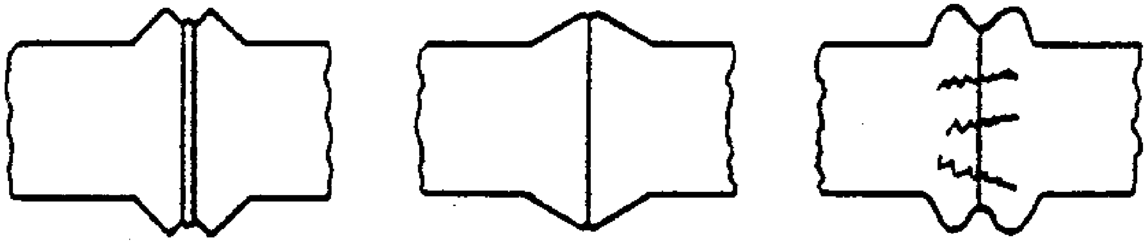
2) Amount and method of contact pressure applied to work-piece by the clamps, such that it has



PROPER CLAMPING DISTANCE (d_1)

EXCESSIVE CLAMPING DISTANCE (d_2)

FIGURE 2.6 Effect of clamping distance on final weld joint quality



(A) CORRECT HEAT AND UPSET

(B) INADEQUATE HEAT AND/OR UPSET

(C) INADEQUATE HEAT INPUT

FIGURE 2.7 Effect of upset and heat on weld joint quality (11) sufficient gripping capability without subjecting the workpiece to surface damage.

3) Heat conduction capacity of grips and method of cooling. This point would also cover material selection as well as physical dimensions.

2.2.2 Upsetting variables. The previous section showed that in order to achieve a strong and sound weld it was necessary for the welding process to exhibit a smooth flashing action for some minimum distance over a given time interval. Weld quality cannot be guaranteed by controlling the flashing variables alone, and so the upsetting variables must also be considered since they are all inter-related. Of all the variables present during the upsetting process, the following are considered to be most influential in the final weld quality:(11)

1) Upsetting Distance
2) Upsetting Rate
3) Upset Current
4) Flashing Voltage Cutoff

These parameters will be studied individually and their interdependence will be demonstrated wherever possible. Some of these variables are fairly well understood while others have not received much dedicated study and research.

A. Upsetting distance

The criteria for establishing the minimum upsetting distance is twofold. One of these requirements is that when the workpiece surfaces are "driven" together there is sufficient upset distance available to force metal-to-metal contact over the entire cross-section of the joint. The second requirement is somewhat similar in that the magnitude of the upset distance must be capable of eliminating all the oxides and molten material that has formed on the abutting surfaces during the flashing operation. This action is accomplished by providing sufficient "stroke" to violently sqeeze out all the inpurities to the exterior surface of the chain link, thereby leaving the joint free of inclusions. The accumulation of this flash material around the link weld need not be removed immediately and is usually discarded at a later stage of the chain production process.

The objective of the selection of the proper upsetting distance is to attain as sound a weld as possible. Part of the overall upsetting process is a forging operation (Figure 2.7), which plays a very important part in the weld quality. From the aforementioned criteria, it could be assumed that the larger the upsetting distance, the better the weld, since it would ensure complete flash expulsion and intimate metal contact. This is not the case, however, in actual performance of welding operations. Investigations have shown(12) that not only is the practice of excessive upset distance impractical from an economic standpoint, but it can also be detrimental to the quality of the weld achieved. The objective of the forging phase is to achieve a metalurgical microstructure at the joint, that is indistinguishable from the base metal. This type of joint, in theory, would possess 100% of the stock material integrity and would ease the problem of predicting the part's reliability. One of the problems caused by excessive upsetting distances is grain re-orientation at the joint during the flow of the metal. As the upset distance increases there is a noticeable increase in the deformation of the fiber structure near the weld line. The fibers become more sharply bent and also the volume of material so affected also increases (Figure 2.8). Some researchers have suggested(14) that this deformation is responsible for the numerous and small heat-affected zone cracks that develop during specimen bend tests.

It should be noted that increasing the upset distance also does not guarantee expulsion of all foreign material. Tests conducted on some AISI 4130 steel specimens showed no correlation between percentage of flat-spots present and the magnitude of the upset. The flat-spots, which are believed to be formed by entrapped contaminants, or by carbon segregation(14) cause an overall degradation of the weld integrity. Hence, in some cases, an increase in upset distance may not improve quality. As a quick summary of the variations

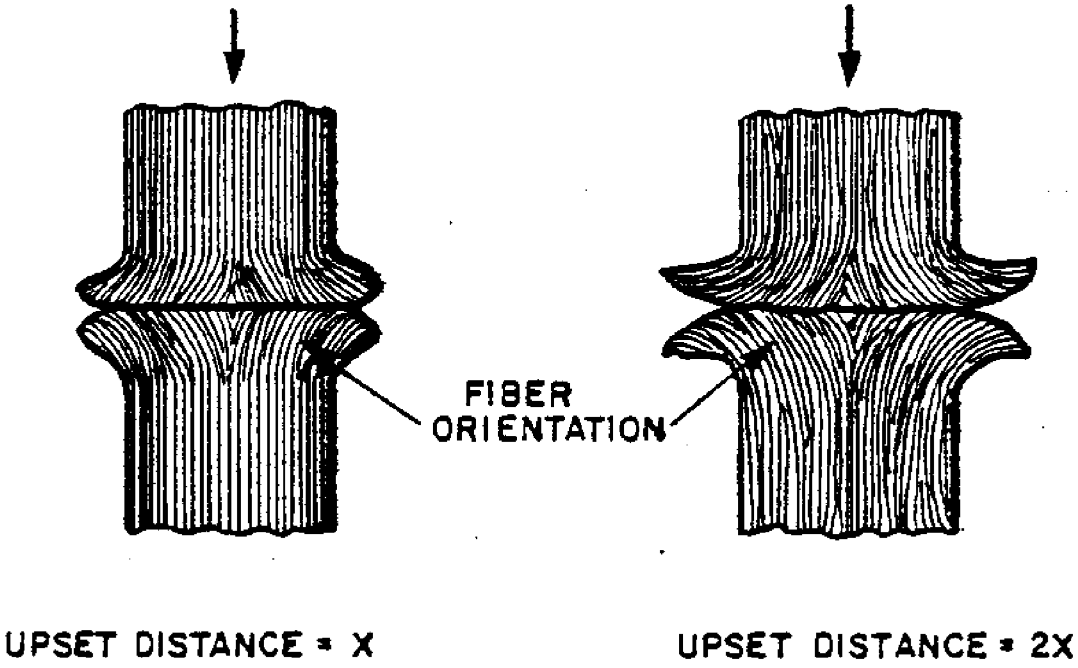


FIGURE 2.8 Effect of upset distance on the orientation of the fiber structure

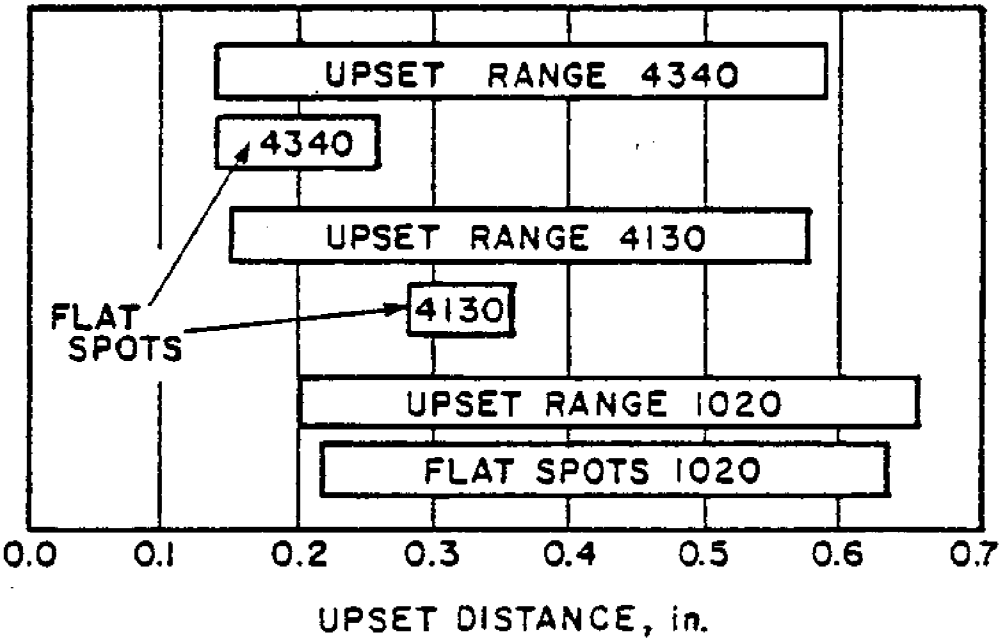


FIGURE 2.9 Effect of upset distance on flat spots in flash welds (14)

that may occur with different steels for different upset distance, Figure 2.9 is provided. In the welding of large anchor chain (AISI 1330), we are dealing most closely with a steel whose carbon equivalent is similar to AISI 4340 and, hence, we would expect similar trends in performance. This may be too broad a generalization, since this assumes that the carbon equivalent is the controlling factor. Since 1330 and 4340 steels vary considerably in their nickel and manganese content, they may exhibit totally different characteristics (see Tables 2.1 and 2.2). To determine the actual response to various upsetting distances it is necessary for the chain stock material to be run through similar testing procedures.

The upset distance is inter-related to other process variables, in that the maximum upset can also be controlled by:

1. Maximum upset force of machine available.
2. Chain link geometry, cross section, material preparation.
3. Amount/method of preheat used.
4. Amount of upset current available.
5. Flashing pattern used.

The amount of upset required to obtain a sound flash weld is related to the variables above and is especially dependent upon the type of metal and section thickness. As a generalization for steel welding, an upset distance of

TABLE 2.1

CARBON STEELS - (NON RESULFURIZED) (15)

(Manganese 1.00 Percent Maximum)

	C	Mn	Pmax	Smax
AISI/SAE 1020	.18/.23	.30/.60	.040	.050

CHECK ANALYSIS TOLERANCES ALLOWED

BARS, BLOOMS, BILLETS, SLABS, AND RODS

Element	Limit Percent	Acceptable (+/-) Percent Up to 100 sq.in.
Carbon	.23	0.02
Manganese	.60	0.03
Phosphorous	.040	0.008
Sulfur	.050	0.008

TABLE 2.2

ALLOY STEELS(15)

AISI/SAE	C	Mn	Ni	Cr	Mo
1330	.28/.33	1.60/1.90	-	-	-
1330H	.27/.33	1.45/2.05	-	-	-
4130	.28/.33	.40/.60	-	.80/1.10	.15/.25
4130H	.27/.33	.30/.70	-	.75/1.20	.15/.25
4340	.38/.43	.60/.80	1.65/2.00	.70/.90	.20/.30
4340H	.37/.44	.55/.90	1.55/2.00	.65/.95	.20/.30

CHECK ANALYSIS TOLERANCES ALLOWED FOR BARS, BLOOMS, BILLETS, SLABS, AND RODS

Element	Limit Percent	Acceptable (+/-) Percent Up to 100 sq.in.
Carbon	0.30-0.75	0.02
Manganese	Up to 2.10	0.04
Nickel	Up to 2.00	0.05
Chromium	0.90-2.10	0.05
Molybdenum	0.20-0.40	0.02

PHOSPHORORUS AND SULFUR LIMITATIONS

Process	Maximum Percent P	Maximum Percent S
Basic Electric	0.025	0.025
Basic Open Hearth/Basic Oxygen	0.035	0.040
Acid Electric/Acid Open Hearth	0.050	0.050

approximately one-half the part thickness is sufficient to promote a good weld.(11)

B. Upsetting rate

In order to produce a high quality flash weld, the upset rate must be fast enough to expel all the molten metal before it solidifies on the abutting surfaces. It can readily be seen that this required rate is therefore influenced by the following:

1) Cooling rate of the chain link at termination of flashing

2) Upsetting distance

3) Upsetting current

4) Physical limitations of equipment

5) Chain link size and geometry with respect to (4)

6) Upsetting force available

Item number 6 may be the greatest contraint to the upsetting rate limitation because the welding machine must apply a force to the movable platen to accelerate the chain link and overcome the resistance of the bar steel to plastic deformation. The available force will therefore limit: the pressure available to upset the metal; the size of the chain link; and the size of the platen. The requirement for a rapid acceleration of the massive platen assembly is a very big problem in the design of large capacity welders.

Once the problem of initial part acceleration has been overcome, we are faced with the actual upsetting portion of the cycle. According to Nippes, Savage and Grotke (16) the upsetting action is actually a two stage operation. During the first stage, over half of the actual deformation occurs at a fairly rapid velocity. With continuation of the upsetting process, the chain link material becomes more resistive to further plastic deformation, which decreases the velocity of the platen. As in any metal forging operation, the resistance of the link material to plastic deformation will be governed by the temperature distribution. As the link temperature increases, the material's yield strength decreases and hence the material can be more easily deformed. This temperature profile, along with the upset pressure available to the equipment, will place a maximum velocity limitation on the platen. Based on the results of weld performance and inspection, the faster the upset rate, the fewer the defects that appear in the weld.

C. Upset current

Upset current is utilized for several different reasons during the welding process. One of these reasons is to provide additional resistance heating to the workpiece to keep a desired temperature profile until the upsetting action begins. This practice is very important in cases where the weld zone may cool too quickly, after termination of flashing, which would result in insufficient upset or cold cracking of the metal. Examples of cases where too high a cooling rate can occur include, but are not limited to, large and odd-shaped parts which may have inherent heat sinks which bring about this condition. Along the same lines of resistance heating, another use of the upset current is to essentially increase the effective capacity of the welding machine. By passing sufficiently high current through a large workpiece, the temperature is increased and therefore the material resistance to plastic flow decreases. This combination allows the welding machine to weld larger pieces than it was designed to perform. In both of these cases, the current value is usually high and is terminated at the end of the upsetting action.

A few other uses of upset current do exist but these usually deal with lower amperage values and their flow may continue beyond the upsetting portion. One of these uses is essentially for postheating the weld of certain alloys to insure that a proper cooling rate is maintained. Another similar use is to assist in the flash removal process by keeping the workpiece at a higher temperature to facilitate trimming of the part. In all these cases, the upset current is activated for a fairly long period of time. It can be concluded from the above, that the duration of the upset current is an important factor in flash welding. Too short of a period will impact on the weld quality by varying the temperature distribution and allowing insufficient upset distance.

The magnitude of the upset current also influences the weld quality because of the resistance heating effect. As the current density increases, the I^2R losses increase, making the metal very soft. Researchers(14) have determined experimentally that, as expected, the upsetting distance increases with increasing current density. Their tests revealed that, on the steels tested, the use of high upset current density produced a corresponding 277% (average) increase in upset distance over specimens tested without upset current (see Table 2.3).

TABLE 2.3

EFFECT OF CURRENT DENSITY ON UPSET DISTANCE

AISI STEEL	UPSET DISTANCE (in.)		PERCENT INCREASE IN UPSET DISTANCE
	No Current	45K AMPS/in^2	
4340	.14	.40	285%
4130	.16	.45	281%
1020	.22	.58	264%

During these tests it was discovered that a threshold current density existed, below which, there was little increase in upset distance for the current used. This implies that a specific amount of heat must be concentrated in this area to raise the average temperature of the quasi-stable temperature gradient above a particular point where the material's ductility increases to any great extent. Hence, there are economic questions which enter here between the trade-off's for using upset currents or larger machines. This decision will be governed by the size of parts, as well as the type of material from which they are fabricated. Energy costs for the high current density requirements may play a major part in the decision process, as well as the fact that certain alloys would require upset current to prevent unfavorable cooling rates (even on small parts). The final selection will be the result of trade-offs conducted in an attempt at arriving at an optimum welding procedure.

D. Flashing voltage cutoff

The final upsetting variable to be discussed is flashing voltage cutoff, and it is one of the easiest variables to define. As the name implies, it marks the termination of the flashing phase and the commencement of the upsetting motion. It is very important that the timing of this phase is regulated to ensure that the abutting surfaces of the link have made complete contact before the flashing voltage cutoff occurs. This control assists in keeping the surface temperatures sufficiently high to be compatible with the following upsetting action. The welding process is more tolerant of an error in adjustment that results in a flashing voltage that continues into the upsetting phase than one that terminates early. By securing the flashing voltage prematurely, the risk is present of developing too rapid a cooling rate which could result in the fomation of a hard, brittle microstructure (i.e., martensite). These formations could later lead to stress concentration sites and crack initiators in the weld zone.

2.3 Relationships of Weld Defects to Welding Parameters

From the previous section, it can be seen that there are many variables which can effect the quality of the flash welded chain link. The variables discussed were process related, so there are numerous other parameters associated with the chain material which have not yet been considered. The selection of optimum flashing conditions requires that the individual understands the inter-relationships that exist between the variables. The final weld quality is strongly tied to these parameters which must be kept within acceptable limits. What the acceptable ranges on these variables are is very hard to define, since they differ for each particular flash welding operation. Certain ranges of parameters in one case would result in an unacceptable weld on another specimen having a different geometry or material properties. Much additional research has to be done in this area to better understand the process, so that optimum welding conditions can be selected in an intelligent manner. It is hoped that eventually this selection process can be accomplished without resorting to the use of experiments or relying upon operator experience.

2.3.1 Flash-butt weld defects.

During the welding process there are many ways in which defects can be produced. These defects can be minimized by rigid process controls, but it is necessary to first identify the types that exist in welded chain. There are two major categories of defects: metallurgical and mechanical. Each of these groups is important, since defects of either type could significantly reduce the chain strength under certain conditions.

A. Metallurgical Defects

1) Flat Spots - These defects are smooth, irregular-shaped areas which are usually visible on fracture surfaces through the weld zone area. It should be noted that these flat spots usually occur in the localized regions of carbon segregation in ferrous alloys. If the welding cooling rate is sufficiently high, these areas of above average carbon concentration can produce brittle martensite. Microhardness tests and metallographic examinations show that this is the case in the areas of "flat spots", and also that

steels with banded microstructures are much more susceptible to this type of defect than unbanded steels.(11)

2) Voids - During welding operations certain conditions can cause the formation of voids within the weld zone. If the flashing voltage is too high, large craters can be created during burn-off which cannot be "filled-in" during the upsetting action. Even in cases where very large upset distances are used, these voids may still be resistant to closure. The void content can cause high stress distributions in the chain link and lower the overall tensile strength of the finished chain.

3) Oxides - Voids can also be created when oxides of the metal are entrapped at the weld interface. These oxides usually accumulate on the abutting link surfaces during flashing and are expelled during the upset phase. Certain alloys produce harder oxides, but in most cases they can be removed by using a large enough upsetting distance. Oxide discontinuities are not too common, but their presence can greatly reduce the strength of the weld

due to their usual brittle qualities.

4) Cracking - One of the more commonly found defects is internal and external cracking. Depending on the type of material used for the chain fabrication, both hot and cold cracking can occur. If the bar stock material has a relatively low ductility over some elevated temperature range, then hot cracking can be a problem. On the other hand, when the base material is a hardenable steel, and the weld is subjected to a rapid cooling rate, the dominant problem becomes one of cold-cracking. Several other types of cracking can occur, the next most common of which is cracking during the upsetting (i.e., forging) operation. In this case, the cracking is caused by the failure to sufficiently heat the chain link to the forging temperature. Under these conditions, the ductility is low and the metal cannot readily flow, resulting in the tearing of the base metal by the upsetting force. Cracking can prove to be a serious defect if the proper conditions are not met. The ends of the cracks are sites for high

stress concentration factors, and, if they are subjected to significant loading, these cracks can begin to grow.

The controlling factor in the determination of the extent to which the weld integrity is affected by the crack is the material's critical crack length. Depending on the fracture toughness of the base steel, this maximum tolerable crack length can range from a fraction of a milimeter in HY-130 steel to a length of several milimeters in aluminum. Fracture toughness (K_{IC}) is a measure for the crack resistance of a material. Some examples of these are shown in Table 2.4 below:

TABLE 2.4(17)

Material	Tensile Strength σ_u	Yield Strength σ_{ys}	Fracture Toughness (K_{IC})
4340 Steel	264 KSI	214 KSI	42 KSI $\sqrt{IN}$
Maraging 300 Steel	268 KSI	250 KSI	82 KSI $\sqrt{IN}$
7075-T6 Aluminum	81 KSI	73 KSI	30 KSI $\sqrt{IN}$

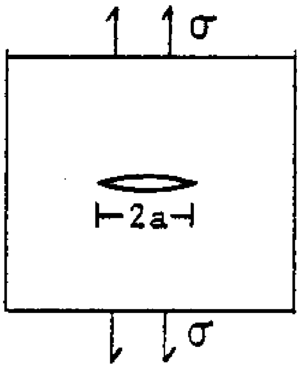
The size of the crack that can be tolerated in the materials in the previous table can be calculated by making some assumptions. Crack extension will occur when the stresses and strains at the crack tip reach a criticle value (σ_c = failure stress). Using the criteria that the material can withstand a 50% reduction in strength before the crack will grow, the following can be stated:

$$\sigma_c = \frac{K_{IC}}{\sqrt{\pi a}} = \frac{\sigma_u}{2}$$

or

$$a = \frac{4\, K_{IC}^2}{\pi\, \sigma_u^2}$$

where a is defined as half the critical crack length.



Using this model, the critical crack length for 7075-T6 aluminum would be 8.8mm as compared to 2.6mm for 4340 steel. If these critical values are exceeded, rapid uncontrolled crack growth could occur, resulting in premature failure of the link. It is also possible to determine remaining link strength as a function of crack length, as shown in Figure 2.10. These plots are idealized in that they consider isolated cracks and do not consider the effects of neighboring flaws. Another complicating factor is the complex loading to which the chain is subjected. All these factors combine and make it quite difficult to establish absolute guidelines for maximum tolerable crack sizes. For the case of typical steels used in 4-3/4 in. anchor chain production, an estimated critical crack length would be around 5mm. This value was based on a stock material with a tensile yield in excess of 68,000 16/in^2 and a minimum elongation of 15.5 percent. The actual criteria for acceptance of anchor chain based on crack content is established by references 18 and 19, but is more qualitative than quantitative in nature.

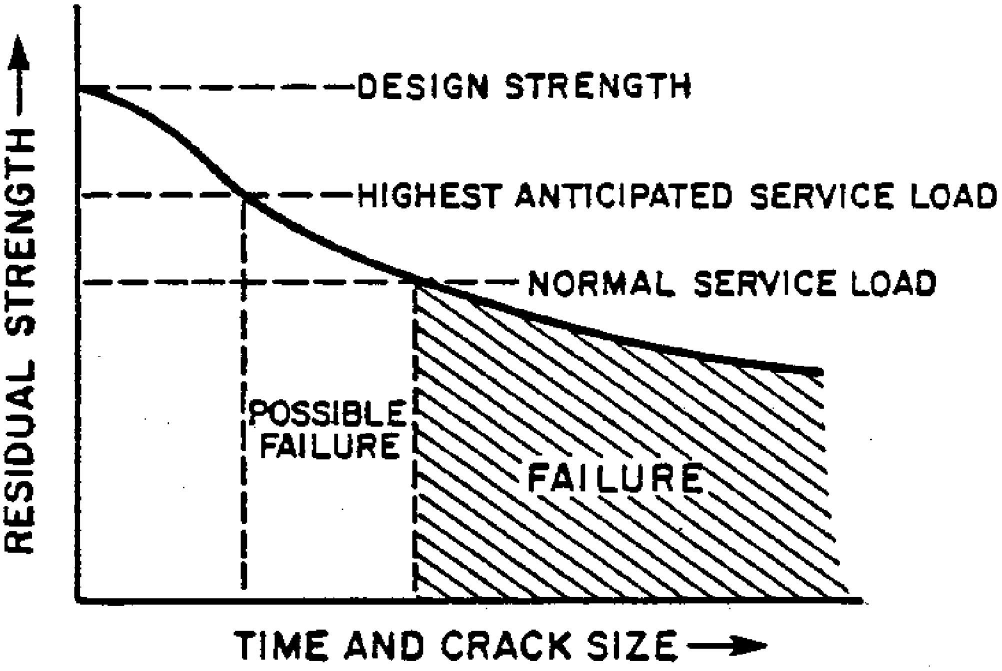


FIGURE 2.10 Effect of crack size on residual strength(17)

5) Bar Stock Structure - Some metallurgical defects can result from the impurities and grain structure of the base metal. Many of these defects can be eliminated by strict adherence to material acceptance standards established in MIL-C-24573(SH) for 4-3/4 in. flash butt welded anchor chain. In accordance with these standards, all steel used in the manufacture of the chain shall have fine-grain structure and may be made by either the open hearth, basic oxygen, or electric furnace process. The chemical composition of the steel shall be determined at the steel mill for each heat of steel and vertified by a chemical or spectrographic analysis conducted by the chain manufacturer. The fusion zone of the flash weld area is limited to an ASTM grain size 5 and it must be free of any form of Widmanstätten structure. If these guidelines are followed, the incidence of base metal defects will be greatly reduced.

Many wrought mill products have an inherent fibrous structure which may cause the bar stock material to have anisotropic mechanical properties. During the upsetting action this fibrous material may be realigned in the weld area (as seen in Figure 2.8) causing a degradation of mechanical properties. One of the properties that is affected is the material's ductility. The decrease in ductility is not normally significant, unless:(11)

(a) The material is extremely inhomogeneous, such as in severely banded steels, and alloys with excessive stringer-type inclusions.

(b) If the bar material is subjected to excessive upset, the fibrous structure may be realigned transversely to the original structure. This condition would considerably degrade the tensile strength of the chain link.

Proper quality control of base metal/bar stock production can eliminate the majority of these problems. Periodic sampling of links can also reveal the presence of a bad supply of base material.

6) Die Burns - These are the last of the metallurgical defects to be discussed. Die burns are caused by local overheating of the chain link at the clamping location. Since the interface between the stock and the clamping die is so susceptible to burning, these surfaces must be kept clean and within close dimensional constraints to avoid damage.

B. Mechanical Defects

Two types of mechanical defects are relatively common in chain fabrication. The first of these is misalignment of the link ends prior to upsetting, and the second is the case of non-uniform upsetting during welding. If the clamping dies and fixtures are not properly adjusted, the link ends may be offset resulting in a non-symetric chain link. This kind of arrangement can cause stress concentrations in the area of the weld. The loading is no longer coaxial and there exists a bending moment at the weld when the link is under a tensile load.

The second case, non-uniform upsetting, may be caused by several conditions. Excessive die opening at the start of upset is a common cause, especially in cases of fairly ductile material. In these instances, the problem can be solved by decreasing the initial die opening distance and appropriately adjusting the welding schedule. Other causes of non-uniform upsetting are insufficient clamping force and link end misalignment. Just as in the previous case, any of these conditions can result in reduced chain strength and life. To minimize the impact of this defect on the quality of 4-3/4 in. chain, a maximum misalignment criteria is established in MIL-C-24573(SH). In accordance with these standards, a maximum diameter misalignment of 3/32 in. is permitted after the flash weld is deburred.

2.3.2 Relationship of welding parameters to weld defects. In an attempt to arrive at a conclusion as to how the welding variables really influence the joint quality, Tables 2.5, 2.6 and 2.7 were produced. From these tables it can be seen that the optimization process can be quite difficult. The variables in all three tables must be considered, and one final selection must be made. As mentioned earlier, it is difficult to place upper or lower bound values on these variables, but some guidelines must be established. A literature search has revealed many sources, which give limited guidance on the variable limits. Since these sources dealt with many types of geometries, materials, and flashing equipment, generalizations were required in order to arrive at any useful conclusions. Table 2.8 is the result of this

TABLE 2.5

FLASHING VARIABLES

WELDING VARIABLE	EFFECT ON THE WELDING PROCESS EXCESSIVE	 INSUFFICIENT
BURN-OFF	* Uneconomical	* Improper temperature gradient
PREHEAT	* Inefficient use of energy * Tendency to decarburize steel	* Difficulty in producing flashing * Insufficient upsetting
FLASHING VOLTAGE	* Large crater formation * Tendency to cause inclusions and flat spots in welds * Higher void content --lower strength * Cast metal in weld	* Metal freezes too early * Inadequate upset distance is achieved with available force * Incomplete expulsion of oxide film and inclusions which gives low quality weld
FLASHING TIME	* Too much heat results in link material becoming too plastic to upset properly	* Insufficient upset due to limited plastic flow
FLASHING RATE	* Freezing of metal occurs	* Insufficient heat is developed to bring metal to the proper upsetting temperature. This is characterized by intermittent flashing
INITIAL CLAMPING DISTANCE	* Alignment problems can arise during upset phase	* Too sharp of a temperature gardient is present which can effect upset distance

TABLE 2.6

UPSETTING VARIABLES

WELDING VARIABLE	EFFECT ON THE WELDING PROCESS EXCESSIVE	INSUFFICIENT
FLASHING VOLTAGE CUTOFF	* Overheating and melting of material	* Improper temperature gradient in link * Formation of "hard" microstructure due to rapid cooling * Insufficient upset distance
UPSET CURRENT	* Overheating/burning * Metal too plastic to upset properly	* Improper temperature profile * Insufficient upset distance * Inclusions and voids * Longitudinal cracking in weld area
UPSET DISTANCE	* Uneconomical * Final parts' dimensions outside specificiations * Excessive plastic deformation causing realignment of microstructure at weld line (flow lines bend towards plane of weld).	* Some oxides remain as inclusions in weld * Voids, cast metal present in welds
UPSET FORCE	* Excessive deformation of chain link (outside specifications) * Weakened weld due to flow lines bent parallel to the weld line.	* Inclusions, voids and oxides present * Insufficient molten metal removal

effort to establish ranges or minimum and maximum values for the process variables. The reader should be cautioned that this is a composite list and some of the limits listed may be unreliable in the generalized sense. Some of these values may be limited to the particular material tested or may exhibit wide variations under different conditions. The purpose of this table was to consolidate references to one location in an attempt to see if any actual, meaningful criteria could be established. As can be noted, the specific applications to large (4-3/4 in.) anchor chain material are labeled to distinguish these applicable limits. It should be stated that most of the criteria listed were obtained through experimentation on small batch samples welded under controlled laboratory conditions. The samples varried in geometry, material properties and represented a sampling of only a small population. Even with all these shortcomings, the table still provides the best existing guidelines to work with in trying to improve flash-butt welded chain.

TABLE 2.7

ANCHOR CHAIN MATERIAL VARIABLES

WORKPIECE VARIABLE	EFFECT ON THE WELDING PROCESS LARGE (HIGH)	 SMALL (LOW)
PHYSICAL DIMENSIONS	* High heat requirements * Large forces * Longer preheat, flash time * Larger upset current	* Less/no preheat * Decreased upsetting force * Smaller energy requirements
DIFFUSIVITY	* Longer initial clamping distance * More chance of parts alignment problems	* Shorter initial clamping distance * Improved control on part alignment
STRENGTH	* Requires more preheat * Larger upsetting force * More susceptible to damage by overheating during preheat * Higher upset currents * Possible post heat required	* Smaller upset forces * Less chance of carbon problems in weld zone
DUCTILITY	* Upset distance increases * Upset force decreases * Flashing time decreases	* Increased force and heat requirements * Insufficient upset distance yielding inclusions or voids
QUALITY OF BAR STOCK	* High quality welds	* Defective weld probability is high

......continued

TABLE 2.7 (cont'd)

ANCHOR CHAIN MATERIAL VARIABLES

WORKPIECE VARIABLE	EFFECT ON THE WELDING PROCESS LARGE (HIGH)	SMALL (LOW)
"HARD" MICRO-STRUCTURE PRESENT	* Low quality weld susceptible to cracking and reduced strength	* High quality weld with few inclusions and approaching the forged uniform microstructure
PHYSICAL MISALIGNMENT	* High stress concentrations can lead to premature failure	* Good joint quality

TABLE 2.8

VARIABLE	ACCEPTABLE RANGE		GUIDANCE	REMARKS
	Minimum	Maximum		
BURN-OFF	$B_c = \dfrac{0.70}{(g_p / \kappa^2)\ \tfrac{1}{3}}$ (min) (10)		* Ensure sufficiently large to acquire suitable stable temperature profile	* f (α, flashing) (9) pattern
PREHEAT	* Facilitate flashing (min) * Avoidance of decarburization (max)		* Held long enough to get uniform heating * Avoid overheating	* Gives flatter temperature gradient
FLASHING VOLTAGE	2V - 16V		* Use minimum possible to maintain good flashing	* These values are below potential required for arcing
FLASHING TIME	* Sufficient to produce the minimum flashing distance (min)		---	* f (secondary voltage rate of metal loss)
FLASHING RATE	* Develop sufficient heat to obtain stable temperature gradient (min) * Temperature gradient is not too steep to allow for insufficient material "softened" for upset action (max)		* Ensure proper temperature gradient is maintained	* Extremely important in the production of sould flash welds

TABLE 2.8 (cont'd)

VARIABLE	ACCEPTABLE RANGE Minimum Maximum	GUIDANCE	REMARKS
INITIAL CLAMPING DISTANCE	* Ensure that selected distance will produce the proper temperature gradient desired (min)	* Once the effective-infinite-clamping distance is exceeded, little gains are made	* f (α, t)
FLASHING VOLTAGE CUT-OFF	* Start of upset motion (min) * After faying surfaces have made intimate contact (max)	* Delayed cut-off is more desirable than early termination	* Can also depend upon upset current requirements
UPSET CURRENT	* High enough current density to give adequate upset and avoid cold cracking (min)	* A current density threshold may have to be exceeded to achieve the desired results	* f (geometry, material, and temperature)
UPSET DISTANCE	* 0.5 of stock thickness (min) * 1-1.25 thickness for heat resistant alloys (max)	* Ensure all oxides and molten material are extruded	* f (material properties and thickness) Reference (9)
UPSET FORCE	Minimum Upset Pressure * Plain carbon steel (.4C max) 10 KSI * Plain carbon steel (.4-1.2C) 15-20 KSI	* Ensure adequate to provide minimum upset distance	* Reference 11

TABLE 2.8 (cont'd)

VARIABLE	ACCEPTABLE RANGE Minimum	 Maximum	GUIDANCE	REMARKS
UPSET FORCE (cont'd)	Minimum Upset Pressure * High temperature alloys 40-50 KSI		---	---
PHYSICAL DIMENSIONS	(Restricted by machine physical constraints)		N/A	N/A
STRENGTH	Minimum tensile yield strength = 68,000 lb/in^2		Test in accordance with:	MIL-C-24573(SH)
	Minimum elongation = 15.5%		ASTM A370	
	Minimum reduction in area = 40%		(Tensile and Charpy V-Notch Tests)	
	Minimum impact strength @ 0°C = 43 ft-lb			
MISALIGNMENT	Maximum diameter overage = 3/32 in.		Maximum acceptable	MIL-C-24573(SH)
GEOMETRY (LENGTH)	121 - 29/32 in. Minimum		Mil Specs 4-3/4 in. chain	* Length over 6 consecutive links
	122 - 1/2 in. Normal			
	123 - 9/32 in. Maximum			

TABLE 2.8 (cont'd)

VARIABLE	ACCEPTABLE RANGE		GUIDANCE	REMARKS
	Minimum	Maximum		
WEIGHT	19475 lb. Minimum 21525 lb. Maximum		± 5% Weight tolerance/shot. No individual link restrictions	N/A

3. Heat Flow in Flash-Butt Welded Anchor Chain

3.1 Welded chain fabrication heat flow models

Since there are so many variables in the flash welding process, the heat flow analysis problem becomes quite complex. All the variables are interdependent and cannot be isolated individually. Previous research has tried to deal with these numerous variables by utilizing dimensional analysis and grouping their effects by parametric equations.(10) As a result of research conducted to date, it appears that one of the dominant factors in obtaining consistently high quality welds has been found to be the development of the proper temperature profile within the link ends, prior to the upsetting action. This quasi-stationary temperature gradient (since the source is continuously moving) can be achieved through various combinations of flashing parameters. In an attempt to lessen the problem of dealing with a large number of variables, a simplified model of the welding process will be utilized. This section will study the heat flow for the entire chain fabricating process. After the overall process is reviewed, the heat transfer mechanisms of that portion of the process, which most effects weld quality, will be modelled.

Looking at the entire chain fabrication process it is possible to distinguish several different heat transfer phases. Depending upon the size of chain being manufactured, the type of bar stock material, and the physical limitations of the welding machine, some or all of these phases may or may not be present.

Phase I - Preheat of bar stock

Phase II - Resistance heating of link end surfaces

Phase III - Development of stable temperature gradient

Phase IV - Upsetting motion/Upsetting current

Phase V - Flash expulsion and cool down.

These five phases could be further broken down to more distinct heat flow areas, but for the overall study of the process this action will not add any knowledge and would only complicate the modeling process. Each of the five phases will be investigated to determine its bearing upon the final heat distribution and weld quality of the chain link joint.

Phase I

Preheating of the anchor link bar stock is the primary purpose of this phase. Since in this manufacturing process the stock must first be bent to form the link, the preheat makes the forming process easier by requiring a smaller force to be applied. Besides the benefits obtained in the forming phase, the preheat also allows for easier flashing due to the increased bar stock temperature. During this phase the bar stock is taken from its storage facility and placed in a heating furnace until the uniform desired temperature is reached (see Figure 3.1). A preselected temperature (T_B) is chosen such that the material's yield strength has been lowered considerably. This action allows the bar stock to be easily shaped into the link form by the force available from the machine. The furnace heating process appears simple at first, but as can be seen from Figure 3.2, the actual heat flow mechanisms are quite complicated. During the early stages of heating, when a large temperature differential exists between the bar stock temperature and that of the furnace, these heat flow mechanisms are especially complex. During this period, the bar could be modeled as being subjected to a line conduction heat source at its point of contact with the furnace surface. Other preheated bars in the furnace could act as radiation heat sources, and there could also be convective heat transfer within the furnace.

Since the objective of this phase of the process is to bring the bar stock up to a desired temperature, the methods of reaching this endpoint are not as important as the resultant temperature. Achieving the correct end temperature is important, since it ensures that residual stresses are controlled during forming, and that flashing can be easily achieved. Some clarification is in order here in that a few limitations must be placed on the preheating to ensure that the stock isn't overheated, or held at a high temperature

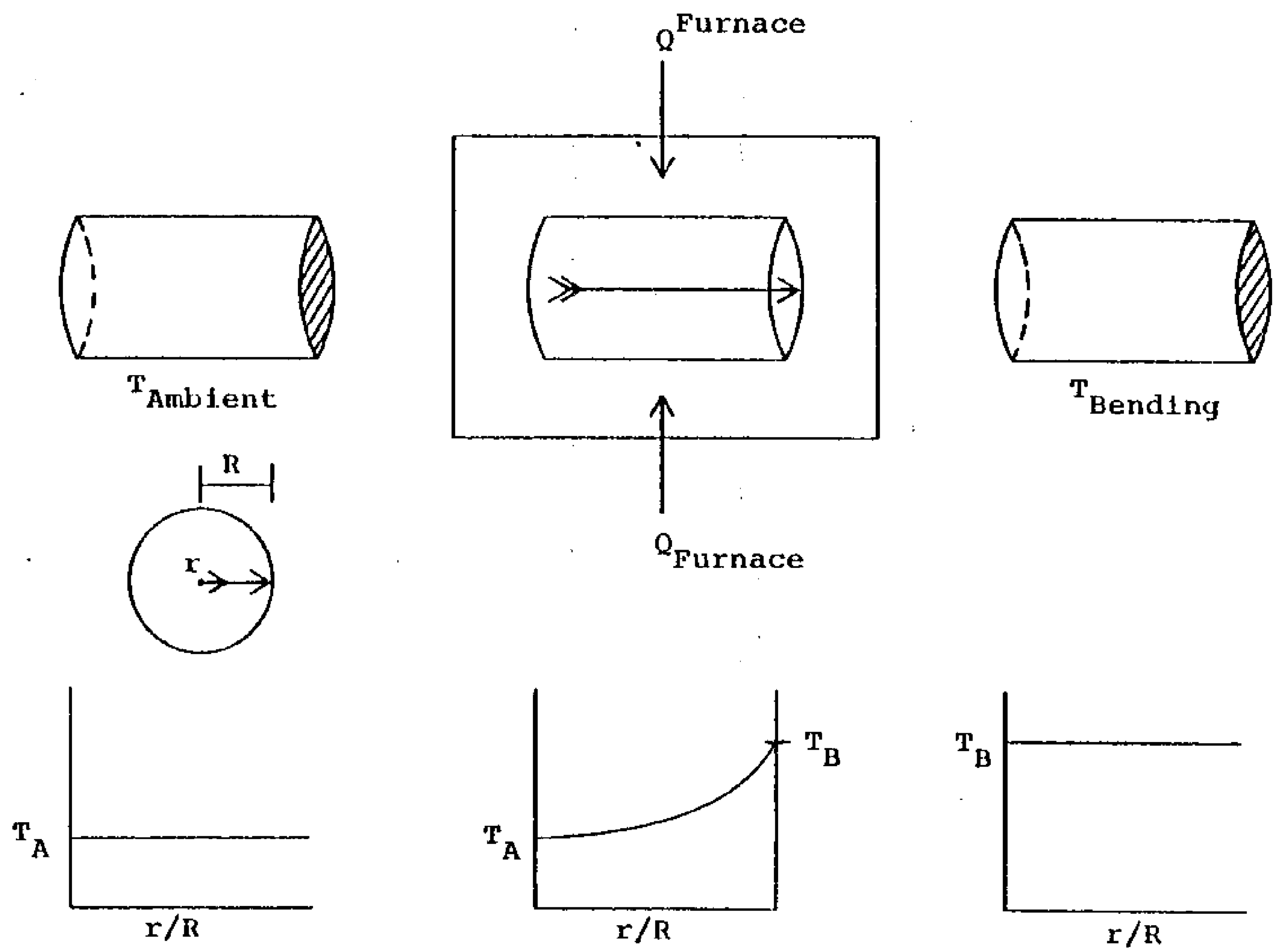
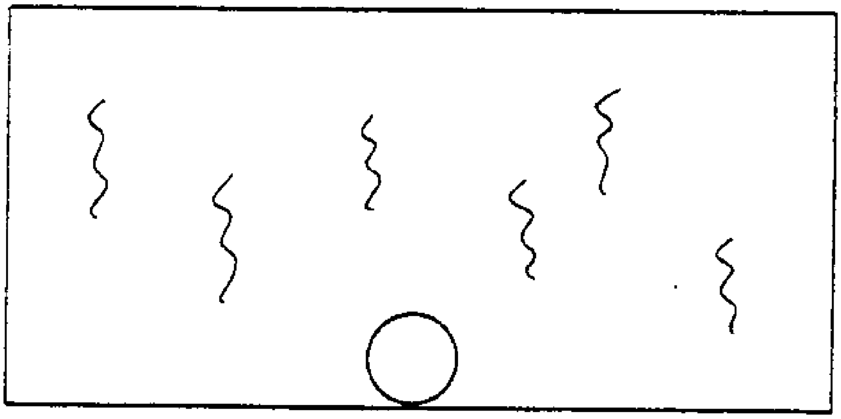
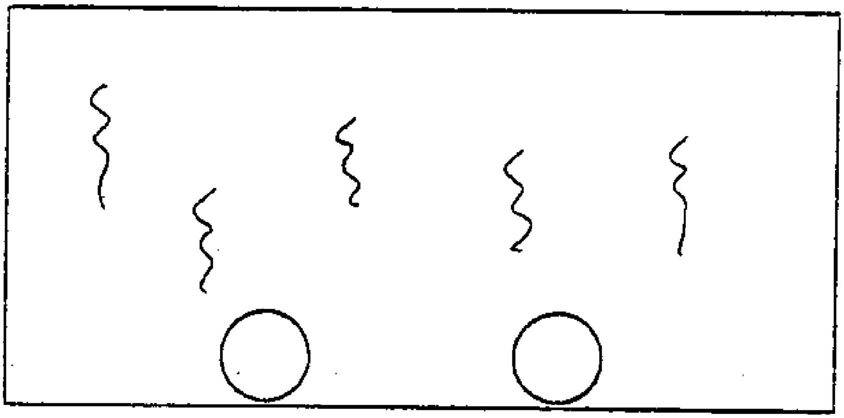


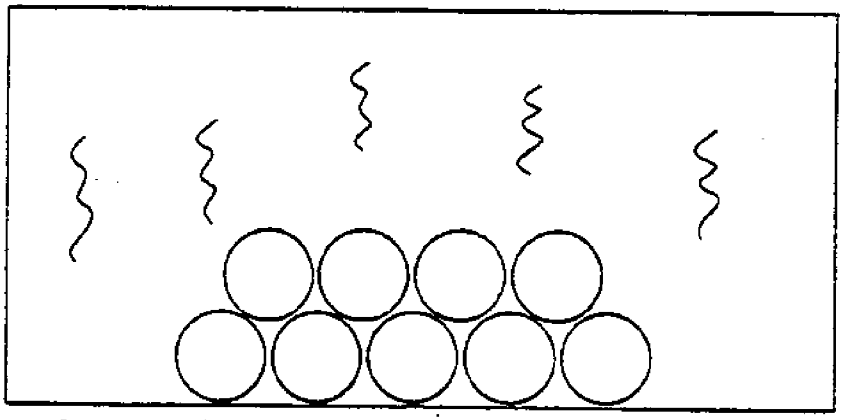
FIGURE 3.1: PHASE ONE - Preheat of Anchor Chain Bar Stock



Conduction Line Heat Source and Radiation from Furnace



Additional Radiation from Other Bar Stock



Complex Conduction, Radiation and Convection

FIGURE 3.2: Methods of Heat Transfer During Furnace Preheat

for too long a time. Either of these conditions could prove detrimental to the weld quality and could cancel the benefits of the preheat process. Because of the relative insignificance of this phase of heat flow on the final weld outcome, it will not be considered as an essential part of the process model. This simplification will have minimal impact on the model results, and should decrease the number of variables that must be considered for the model.

Phase II

Once the link material has been sufficiently preheated, the flashing voltage can be applied across the workpiece and the selected platen flashing pattern can be activated. As the platen motion begins (closing phase) an initial bridge is formed and resistance heating begins to raise the temperature of the surface protuberances (see Figure 3.3). When sufficient heat has been generated, the small amount of metal will melt and be expelled by the induced magnetic field around the bridge. Once the current path is disrupted, a small arc occurs between the interfaces at the location of the expelled material. This phase of the heat transfer is again quite complex, but could be simplified by modeling the initial resistance heating as depicted in Figure 3.3c. Under actual conditions, the contact bridges would be of different dimensions (diameter, length, or incomplete contact, as shown in Figure 3.3b) and would pose

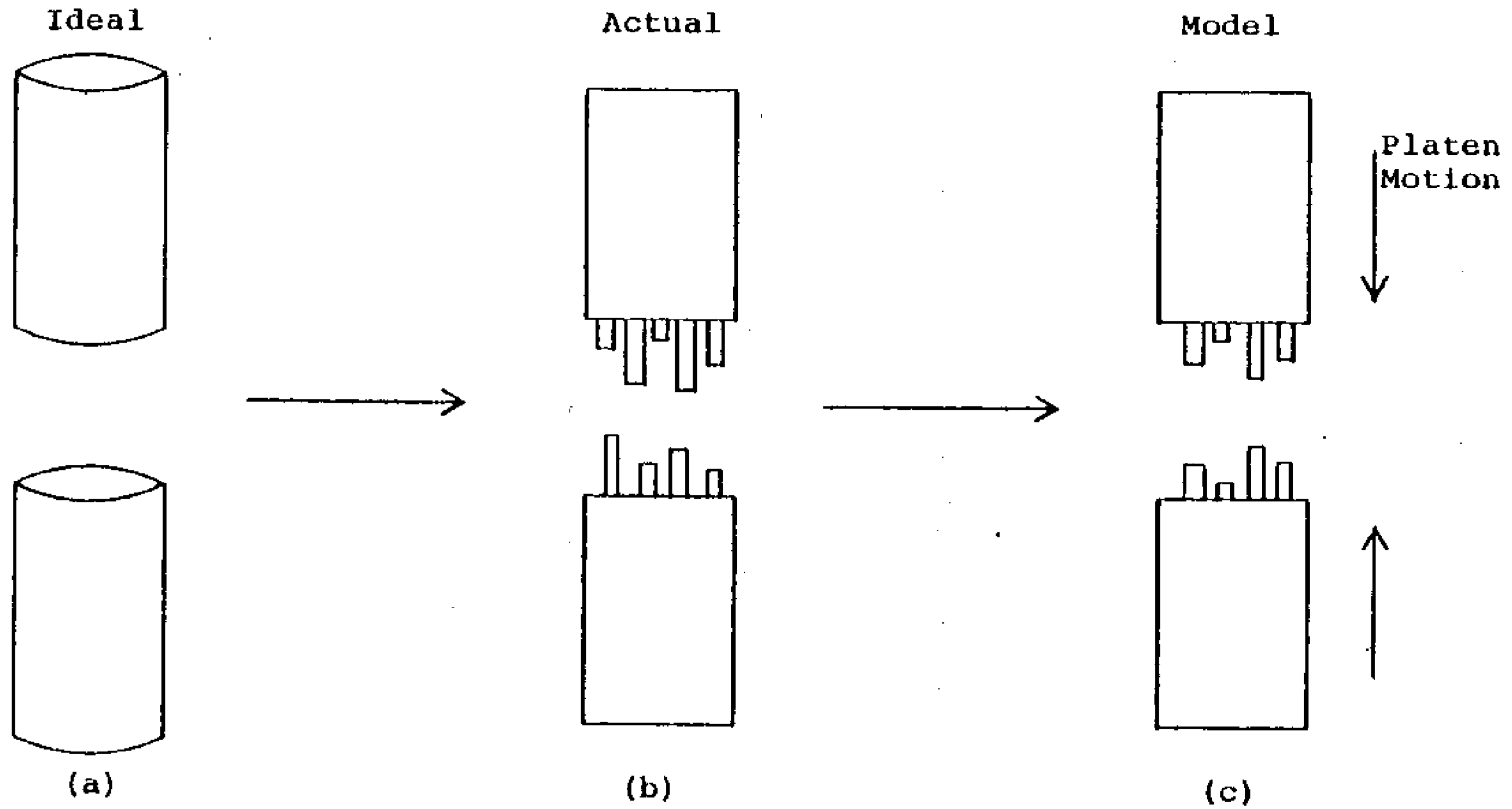


FIGURE 3.3: PHASE TWO - Modeling of Bridge Formation
Prior to Flashing

a very complex scenario to analyze. As a first attempt at simplifying the model, it can be assumed that the following conditions exist during the resistance heating phase:

1) Bridges can only occur one at a time, and their location of formation is determined by random distribution.

2) Opposing protuberances are "mirror" images of each other, such that physical dimensions and alignment are identical as the platen advances with time.

3) The physical dimensions of the contacts will be small with respect to the overall link dimensions.

4) Bridges will be formed and broken at such a rate that continuous conductive heating of the abutting surfaces will take place. The areas adjacent to the contact points will develop isotherm patterns which, with time, will progressively overlap each other (Figure 3.4), constantly increasing the average surface temperature.

5) During this phase, the platen motion will occur at such a rate as to provide sufficient heating to bring the required amount

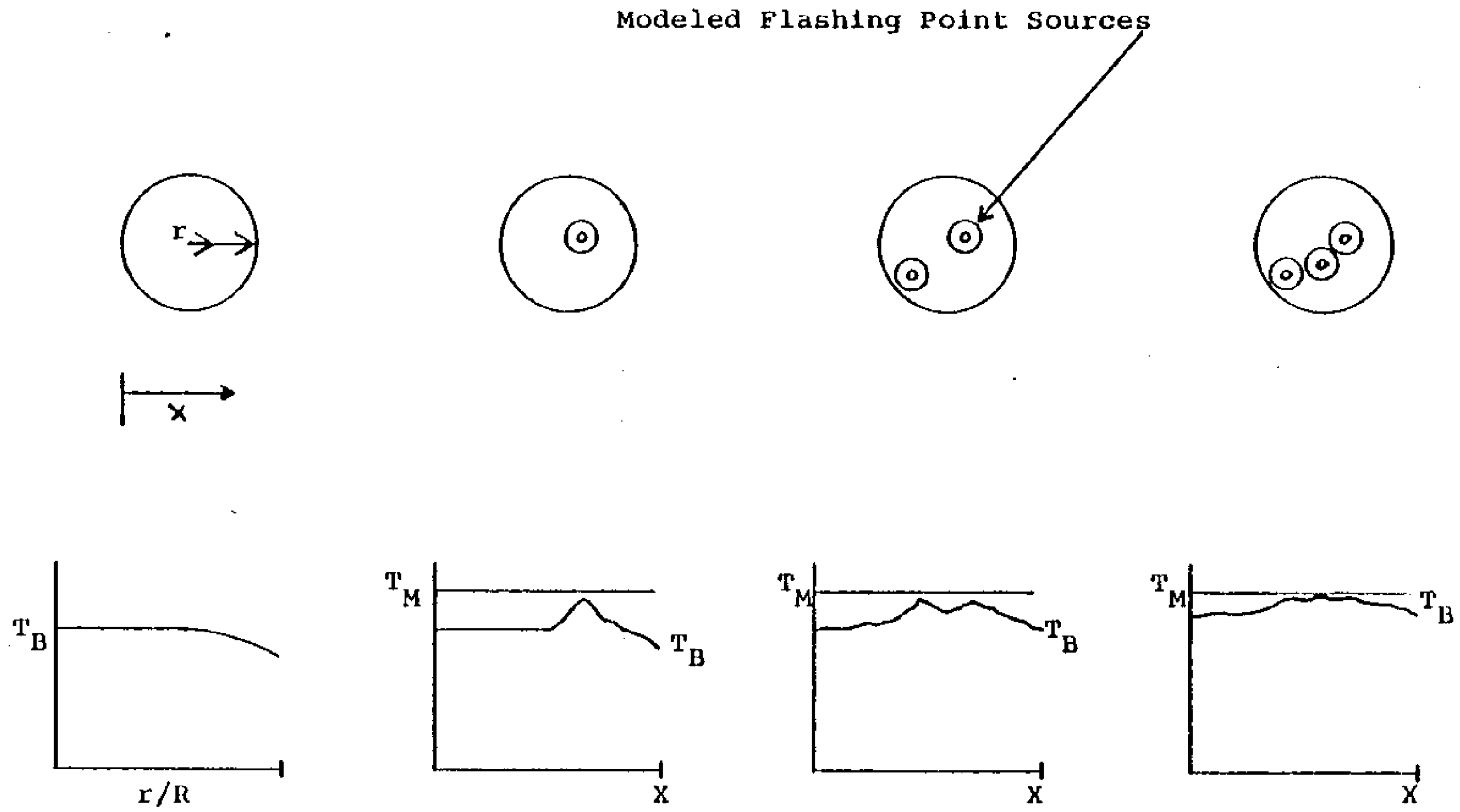
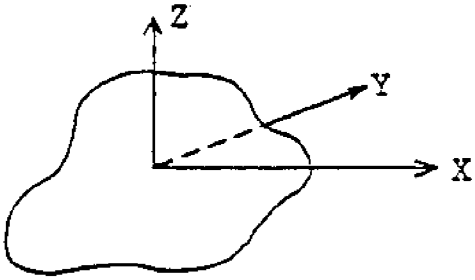


FIGURE 3.4: PHASE TWO - Commencement of Point Source Flashing at Interface

of material up to "burn-off" temperature.

6) The arcing that occurs after the metal expulsion provides some heat input to the system but it will be neglected due to its complexity.

A valid model, based on the aforementioned assumptions, would be that of heat conduction due to an instantaneous point heat source that is randomly located around the surface as a function of time. This initial model would assume radial heat flow, as shown below,



and whose solution would be of the form:(20)

$$T - T_0 = \frac{q}{c\,\rho} \cdot \frac{e^{-\frac{r^2}{4\kappa t}}}{(2\sqrt{\pi\kappa t}\,)^3}$$

where $r^2 = X^2 + Y^2 + Z^2$

The problem with this model is that, since the point source is randomly located around the workpiece surface at a very rapid rate, the temperature profile of the surface becomes very complicated. Within a very short period of time the isotherms from individual point sources begin to overlap and it is virtually impossible to obtain the actual T_0 at the next point source location. Since the overall effect is to rapidly raise the surface temperature to the desired gradient, the individual point sources would eventually approach the equivalent of a moving planar heat source acting at the surface of the workpiece. This quasi-stationary state would exist when the abutting surface's average temperature has reached the approximate melting temperature of the anchor link material.

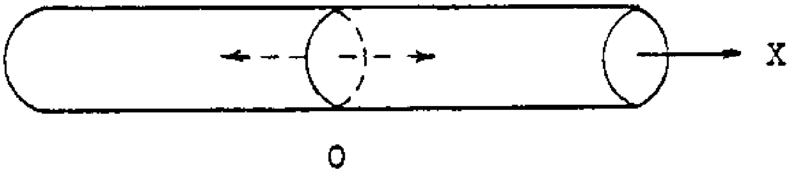
An over-simplification of this phase could also be modeled as an instantaneously applied planar heat source in the bar stock. This model would assume that the following conditions exist, at least momentarily:

1) Heat is supplied instantaneously to the entire bar end surface.

2) Both ends of stock make complete intimate contact.

3) The closing/upsetting platen motion has zero velocity at the time of the heat source application (stationary heat source)

These assumptions would allow the cumulative effect of the numerous point sources to be summarized into a single large heat source at a later stage of the actual process. (This would establish a new time zero in the model.) The specific solution to the preceeding problem is as follows:(20)



0 = Plane of heat source location

<u>Assumptions</u>:

1) Heat is supplied instantaneously and uniformly on a plane;
2) Heat flows only in the direction normal to the plane where heat is supplied

<u>Solution</u>:

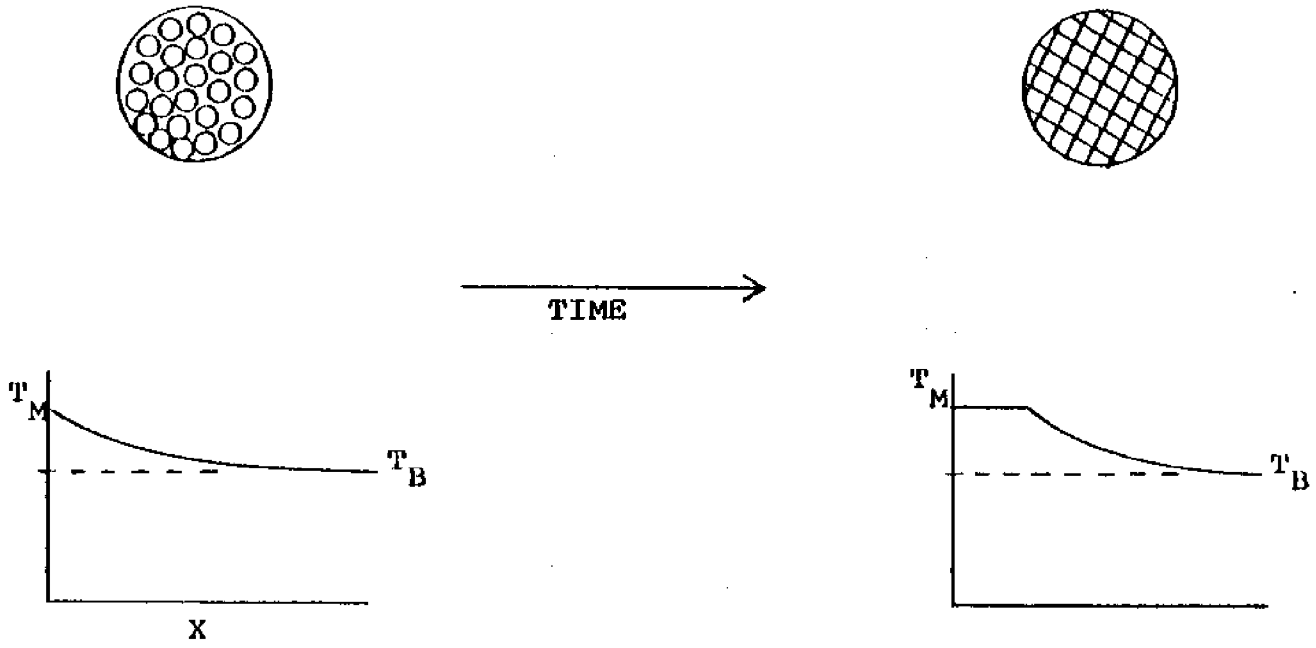
$$T - T_0 = \frac{q}{c\,\rho} \cdot \frac{e^{-\frac{X^2}{4\,\kappa t}}}{2\sqrt{\pi\,\kappa\,t}}$$

q = heat supplied per unit area

Because the end result of this phase is really a quasi-stationary thermal state, with the average interface temperature approaching the material's melting point, the relative importance of this portion of the welding process was re-examined. Of all the variables present during this phase, the one which most influences the quality of the end-product has been shown to be the flashing voltage. This voltage should be kept at a minimum to reduce the probability of producing large craters near the abutting surfaces. Since the actual heat transfer methods do not significantly effect the overall outcome of the weld quality, this phase need not be modeled. The impact of not including this portion of the heat transfer process would not result in an unrealistic model, and at the same time, would greatly simplify the modeling task.

Phase III

The early stages of surface melting and the development of a stable temperature gradient are the major components of this, the third phase of the heat transfer process. During this phase the quasi-stationary temperature gradient, which is so important for the production of high quality welds, is developed as the burn-off of stock material takes place. The platen flashing pattern motion, combined with the controlled burn-off, results in a constantly moving heat source which manages to produce sufficient heat input to counter-balance the heat flow out through the grips. Welding parameters are preselected such that the anchor link material will attain a temperature profile which allows a specified amount of material to be heated above the required forging temperature (see Figure 3.5). By doing this, the required upsetting forces are decreased and



X = Depth into Specimen

FIGURE 3.5: PHASE THREE - Bringing Average Interface Temperature Up to the Material's Melting Point

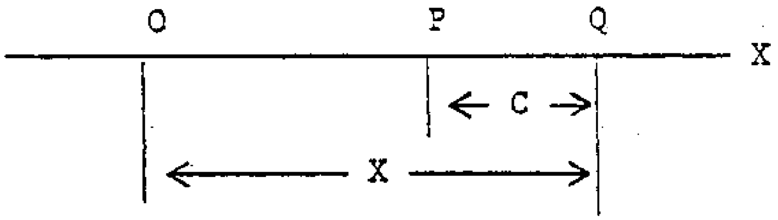
adequate upset distance can be obtained to ensure a good weld line. This required stable temperature gradient can therefore be modeled as a heat conduction problem in a quasi-stationary state since the platen and, hence, the planar heat source are both moving (due to burn-off).

Because of the importance of this phase of the heat flow process, it is necessary to develop a model to deal with this state. The model consists of a moving planar heat source located in the bar stock. The following assumptions are made for the analysis:

- Size of the heat source is small with respect to the chain link overall dimensions.
- The chain link material is uniform and isotropic in the thermophysical properties.
- The moving heat source's intensity is constant with time. This is an over-simplification, which will be addressed later.
- Conduction is the only mode of heat transfer.
- The heat source is moving either at a constant velocity, or at constantly accelerated motion.
- Thermophysical properties are independent of material temperature.

The above assumptions are not unrealistic, with the exception of the constant intensity heat source, and they offer a means of simplifying the heat flow model. The model can be shown as follows:

Moving Planar Heat Source(20)



O: Original point where a heat source starts

P: Location of the heat source at reference time

Q: The plane in consideration

Solution:

$$T - T_0 = \frac{q}{C\rho v} \cdot e^{-\frac{V}{2\kappa}(\xi + |\xi|)}$$

where $\xi = X - vt$

q = heat supplied per unit area and unit time

This model is not exact since in the real state the heat flow is not achieved until an infinite time passage has occured. Another shortcoming is that the heat source actually varies with the velocity and acceleration of the platen. For simplification, the process can be considered in a quasi-stationary state after a reasonably short period of time has elapsed. A more realistic model of this phase will be developed in Section 3.2.

Phase IV

The upsetting motion of the welding process is the fourth phase of the heat flow in the chain link. During this phase one of two alternative paths can be followed, depending upon the type and size of chain being produced. Figure 3.6 depicts these available paths and shows the effect of upset current on the temperature distribution within the chain link. Without the upset current, rapid cooling rates can occur that could cause weld defects in certain types of chain. The rapid cooling could cause a hardened surface layer to be formed that would interfere with the upsetting action. Another possibility is that a hardened micro-structure could be formed (i.e., martensite) which could become entrapped in the weld and cause stress concentration factors and crack formation sites. For this reason, the one alternative is to use an upsetting current to maintain the desired temperature profile during the upsetting phase.

Since during this phase the heat source can be considered as being applied at the grip electrodes, the actual model for heat application then becomes a function of the electrode contact shape. This shape can be a point surface contact, a line contact or an annulus type of arrangement. For simplification, it can be assumed that the heating source is a planar source located at the grips with a heat flow perpendicular to the plane. This type of model would

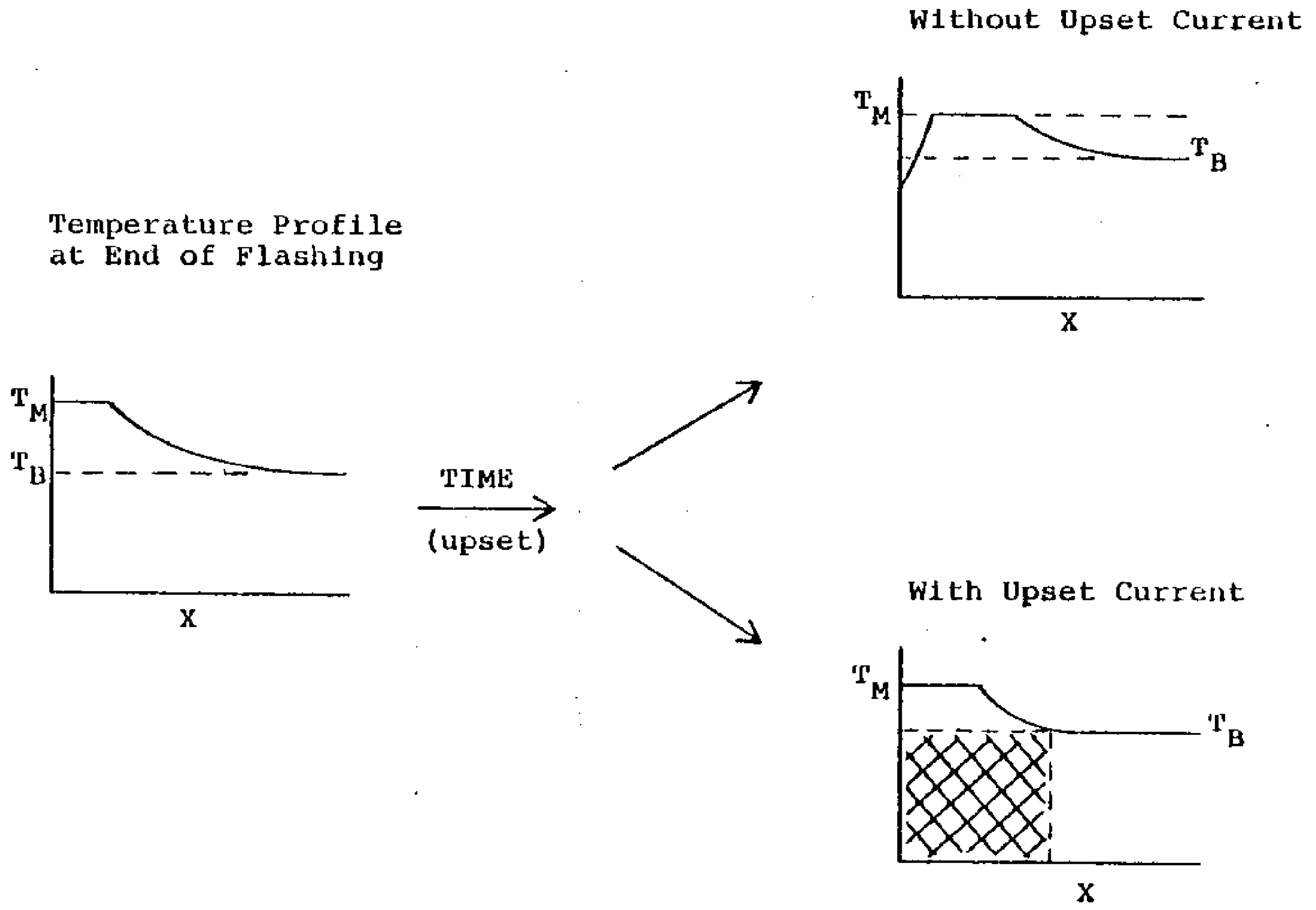


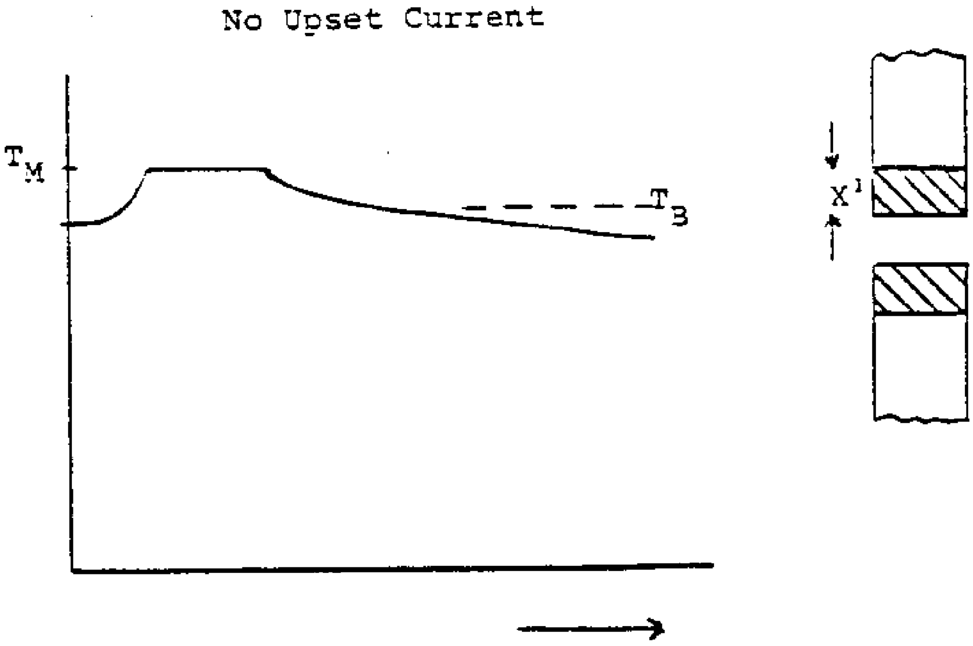
FIGURE 3.6: PHASE FOUR - Heat Profile Prior to Upsetting Action

result in a stationary heat source located at a specified distance from the abutting surface. Assumptions and equations would be identical to those described for the planar heat source in phase two. The main difference would be in the heat input requirements, since less heat input would be needed during the upset phase.

If a large time delay is encountered before the upsetting begins, the weld quality can be drastically affected by this phase of the heat flow and, hence, the correct profile must be maintained. Since the duration of this phase is usually very short, including this portion in the model would not produce any additional information that is critical to the overall weld cycle. Because of these factors, this area of heat flow will be ignored and it will be assumed that the chain link does not undergo any appreciable temperature change during the platen's accelerated upsetting action. With this assumption, the problem of inclusions and cracking can be minimized.

Phase V

The final heat flow phase entails the actual upsetting action which causes (see Figure 3.7) flash to be expelled. and the cool down period that follows. The rapid motion of the platen, combined with the upsetting force, causes the molten metal and oxide layer to be violently expelled when the abutting surfaces of the link make contact. The



X^2 is greater than X^1

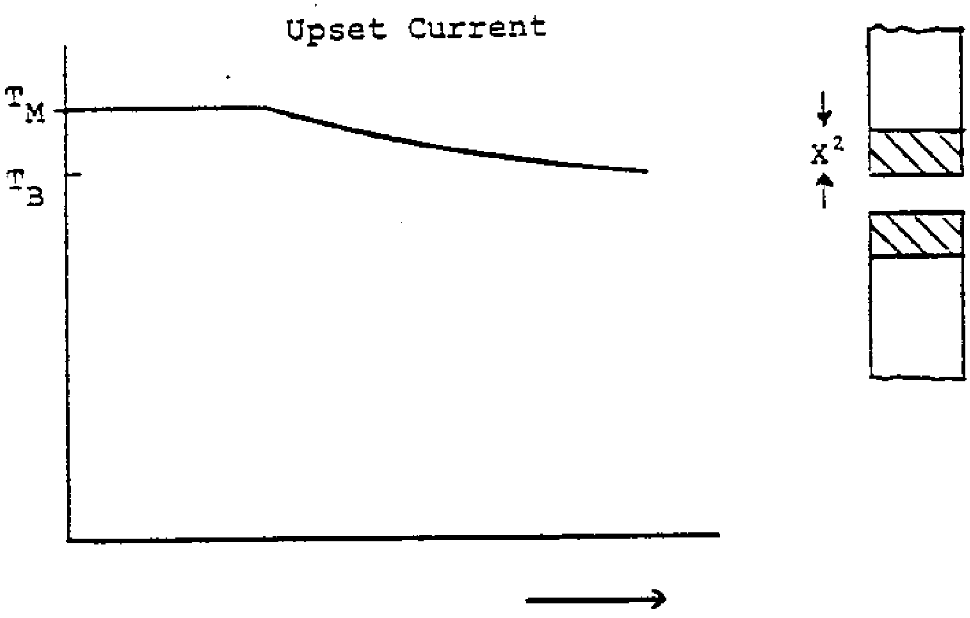


FIGURE 3.7: PHASE FIVE - Upsetting Action
With/Without Upset Current

temperature profile that exists prior to upset is very critical in ensuring that an adequate upset distance can be achieved. Since the upset time is very short, the temperature profile during this phase has little time to change and influence the final weld quality. As with many of the other phases of the fabrication process, this area can be ignored without degredation of the heat flow model.

3.2 Modeling the critical heat flow

As discussed in the previous section, the most critical portion of the heat transfer for the chain manufacturing operation occurs during phase three of the process. During this phase, a quasi-stationary temperature profile is developed after a certain amount of burn-off has occured. Little or no change occurs in this profile during a period of time that follows, and it is within this time span that the upsetting action should take place. The size of the stable temperature region allows for some error in the initiation of the upsetting phase without degradation of weld quality.

Upon further investigation of this phase of heat transfer, it was realized that the original proposed model was a gross oversimplification of the actual condition. The dominant error was centered around the assumption that the heat source maintained a constant intensity. In reality, the amount of heat present is a function of the size of the bridge contact area, voltage, and platen velocity. The intensity of this heat source is constantly changing and is very complex in nature. As a simplification of this heat source, it will be assumed that it can be modeled as an instantaneously applied planar heat source moving at constant velocity or acceleration. In this model the amount of heat provided by the source will be considered to be a function of the platen velocity and independent of the geometry of the contact areas.(10) This appears to be a reasonable assumption since to maintain flashing the burn-off rate, and hence heat input, must increase with increasing velocity.

Starting with the assumption that conduction is the only significant form of heat transfer in the flashing process, a relatively simple model can be developed which still exhibits the basic characteristics and responses of the actual flashing process. The general equation of heat conduction in a solid is:(21)

$$\frac{\partial}{\partial X}\left(\kappa \frac{\partial T}{\partial X}\right) + \frac{\partial}{\partial Y}\left(\kappa \frac{\partial T}{\partial Y}\right) + \frac{\partial}{\partial Z}\left(\kappa \frac{\partial T}{\partial Z}\right) + W_i = \rho c \frac{\partial T}{\partial t} \tag{3.2.1}$$

where,

W_i = heat generation per unit volume and time (BTU / ft^3 hr)

If the thermal conductivity κ is assumed constant with time, and no internal heat sources are present, the preceeding equation can be simplified to:

$$\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} + \frac{\partial^2 T}{\partial Z^2} = \frac{\kappa}{\rho c} \quad \frac{\partial T}{\partial t} \tag{3.2.2}$$

By considering the flashing interface as the only heat source, it can be assumed that a temperature distribution will only exist along the long axis of the chain link. Hence, small heat losses to the surrounding area are neglected and equation 3.2.2 can be further simplified to a one-dimensional system described by:

$$\alpha \frac{\partial^2 T}{\partial X^2} = \frac{\partial T}{\partial t} \qquad (3.2.3)$$

Since during the flashing process the end surfaces of the chain link melt away, the location of the heat source is constantly moving along the X-axis. As a means of simplifying the model, it is more practical to relate the heat flow to a moving coordinate system located at the flashing interface. By defining ξ as the instantaneous distance from the flashing interface, and by letting the burn-off per specimen at any time equal $B(t)$, the following relationship can be established to relate the stationary and moving coordinate systems:

$$X = B(t) + \xi \qquad (3.2.4)$$

With this, equation 3.2.3 can be transformed to:

$$\frac{\partial}{\partial \xi}\left(\alpha \frac{\partial (T-T_0)}{\partial \xi}\right) + V \frac{\partial (T-T_0)}{\partial \xi} = \frac{\partial (T-T_0)}{\partial t} \qquad (3.2.5)$$

In considering an intermediate time (t') in a selected time interval ($0 < t' < t$), it can be seen that the burn-off per specimen at this time is B(t'). The following formula can be developed to show the relationship between the intermediate and final instantaneous distances ξ and ξ'.

$$\xi' - \xi = B(t) - B(t') \qquad (3.2.6)$$

Assuming that the amount of heat dissipation at this intermediate time is q(t'), than during a small time step dt', a quantity of heat equal to their product will raise the temperature of the material at a distance ξ by an amount $d(T-T_0)$.(10) The quantity $(T-T_0)$ can be redefined as θ, and so the equivalent temperature rise can be expressed as $d\,\theta$.

Carslaw(22) formulated a solution for a moving planar heat source, which gives the following solution for the temperature rise at a particular instantaneous distance from the flashing interface.

$$\theta = \frac{1}{2\,\rho c\,(\pi\kappa)^{\frac{1}{2}}} \int_0^t e^{\frac{-(\xi')}{4\,\kappa(t-t')}} \cdot \frac{q\,(t')}{(t-t')^{\frac{1}{2}}}\,dt' \qquad (3.2.7)$$

One difficulty in attempting to solve the above equation comes from the complexity of describing q(t'). Savage (10) assumed that the time rate of heat input to the workpiece is proportional to the heat input. Hence, as an approximation, he arrived at the following:

$$q\,(t') = m\,V \qquad (3.2.8)$$

His investigation into the area of the rate of heat dissipation in flashing concluded that the proportionality constant (m) in (3.2.8) was found to be;

$$m = 2\,\Theta_m\,\rho c \qquad (3.2.9)$$

where Θ_m is the temperature difference between the initial and melting temperature of the material. These assumptions seem valid for the model, so they will be utilized in solving for values of Θ.

Two types of models were required, linear and parabolic flashing patterns. In order to obtain the actual equations, the equations for m, $q(t')$, and ξ' were substituted into EQN 3.2.7, and the final forms of the equation appear below.

Linear model

$$\Theta = \frac{.5\,U_p\,\Theta_m}{(\pi\,\kappa)^{\frac{1}{2}}} \int_0^t e^{\frac{-(\xi + .5\,U_p(t-t'))^2}{4\,\kappa\,(t-t')}} \cdot \frac{dt'}{(t-t')^{\frac{1}{2}}} \qquad (3.2.10)$$

where U_p is the value of the platen constant velocity.

Parabolic model

$$\Theta = \frac{.5\,G_p\,\Theta_m}{(\pi\,\kappa)^{\frac{1}{2}}} \int_0^t e^{\frac{-(\xi + .25\,G_p(t-t'))^2}{4\,\kappa\,(t-t')}} \cdot \frac{t'}{(t-t')^{\frac{1}{2}}}\,dt' \qquad (3.2.11)$$

where G_p is the value of the platen constant acceleration.

Equations 3.2.10 and 3.2.11 were used to develop a computer model to generate temperature profile curves that could be expected to be present during flashing.

An interactive computer program, written in FORTRAN, was developed on the basis of the linear and parabolic flashing pattern temperature equations (see Appendix A for a complete listing of the program and for the outputs obtained from sample runs). The purpose of the program was to produce a useful mechanism for determining how changes in various flashing parameters affected the temperature profile that was developed during the flash welding process. A second objective was to provide a means for obtaining heat flow patterns, without having to resort to experimental data collection. The initial version of the program was simplified by assuming that all material properties were constant with temperature. Later versions were upgraded to include the capability of altering thermal diffusivity with temperature during the process (see below for details).

The program consists of a main program and four subroutines. The main program, called HEATCON, requires that the user select the type of flashing pattern and then input values for a number of variables as follows (see also Figure 3.8):

- Constant velocity, U, if linear flashing, or constant acceleration, G, if parabolic flashing.
- Values of the thermal diffusivity (of the material under consideration) at ten preselected temperatures which cover the range of the expected temperatures to be calculated by the program.
- The initial temperature, TI, which can be different from the ambient temperature if preheating is used.

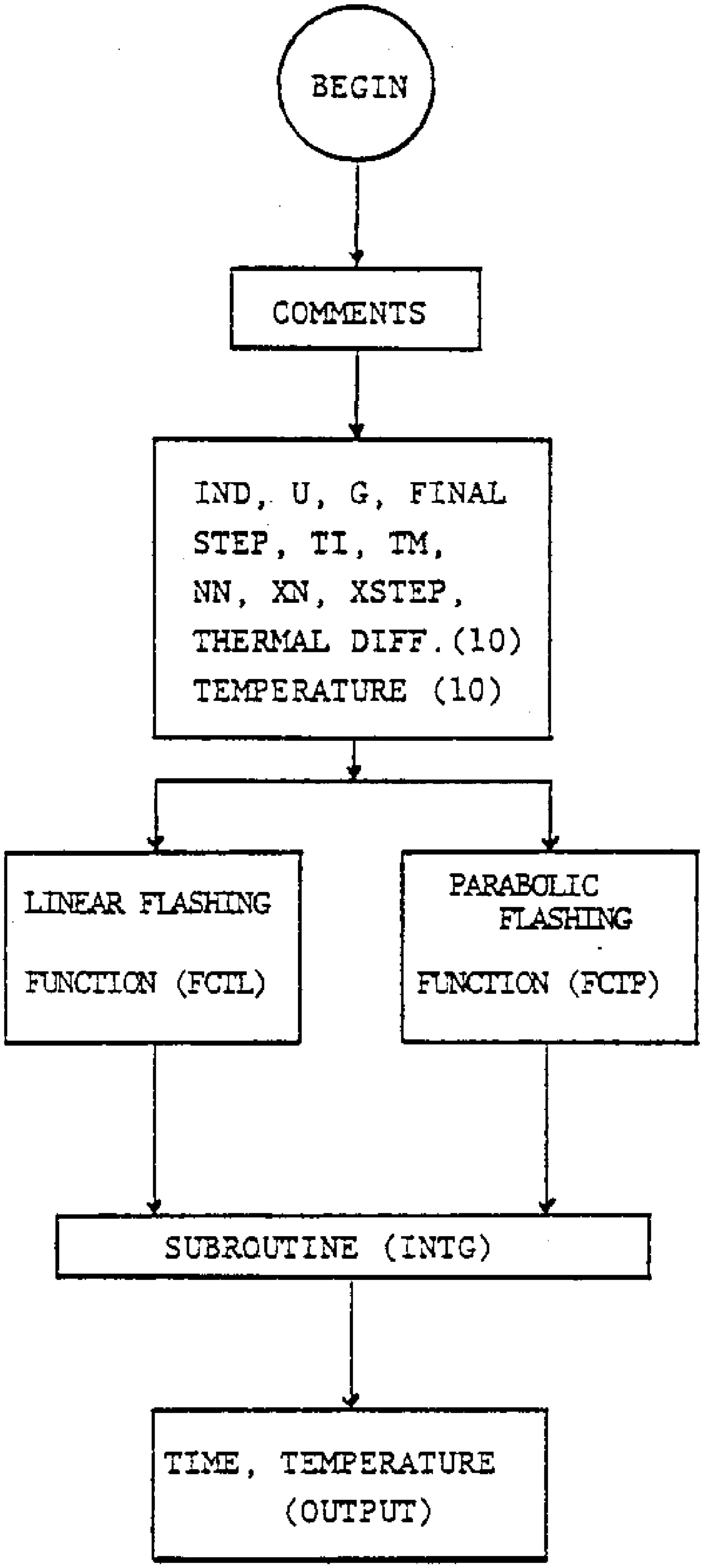


FIGURE 3.8: Main Program Flow Chart

- The melting temperature of the material under consideration, TM.
- The total time interval from the start of flashing, FINAL, for which calculations are desired.
- The time step, STEP, to be used in the numerical integration subroutine INTG.
- The number of points along the x-axis, NN, for which temperature histories are to be calculated; their instantaneous distances from the flashing interface are determined by the value of the first point's instantaneous distance, XN, and their uniform spacing, XSTEP.

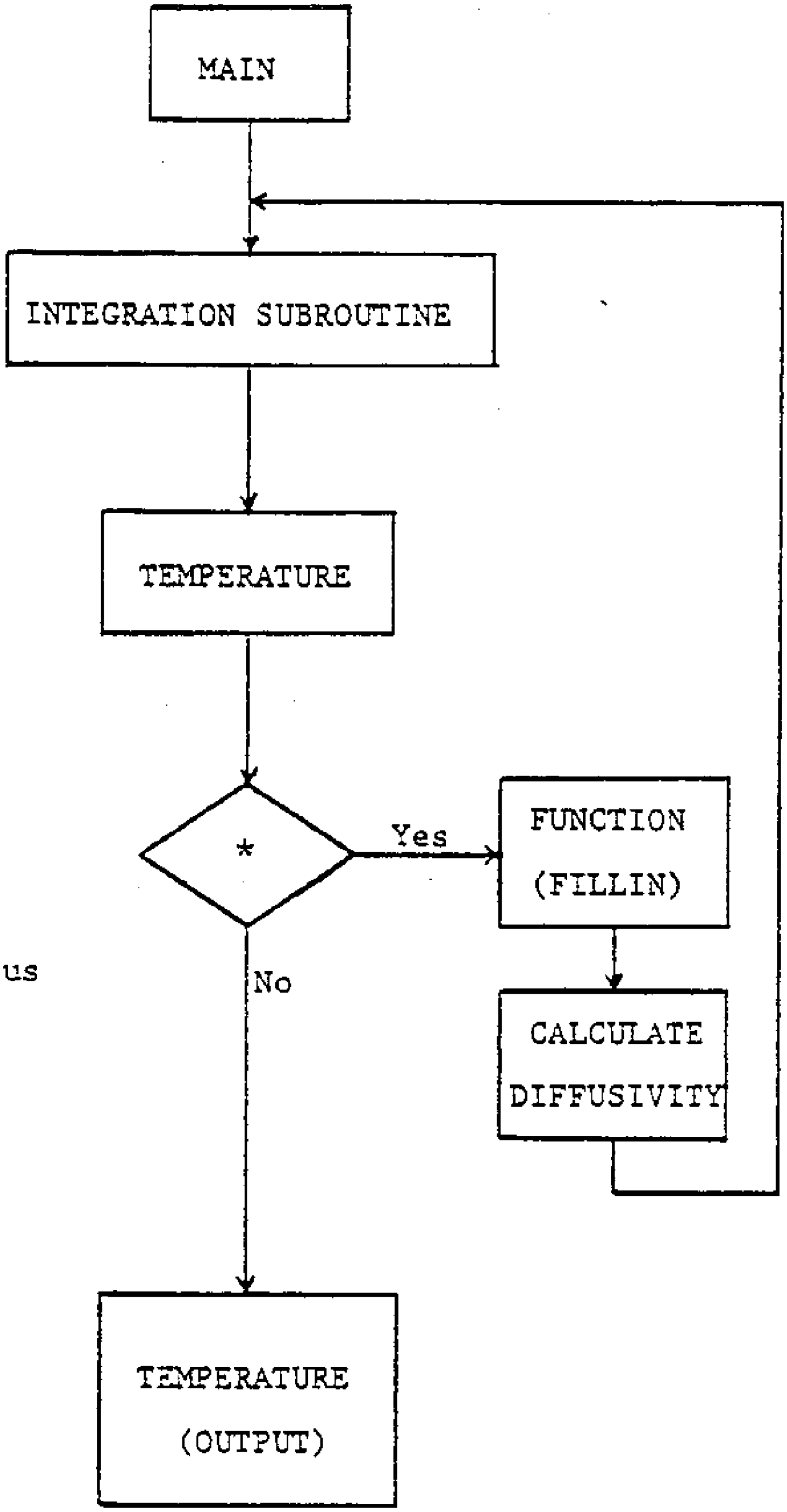
All required numerical integrations are performed by the integration subroutine INTG. The calculations are made by means of the ten-point Gauss quadrature formula.(23)

The program allows for the temperature dependence of the material thermal diffusivity, on the basis of an iterative process, as follows:(24) In the input phase of the computer program ten values of temperature, ranging from the ambient temperature to the material's melting temperature, are read in. Following this, ten values of the material thermal diffusivity, corresponding to the ten temperature values, are also read in. From these data, it is possible to evaluate the thermal diffusivity at any temperature with the aid of FILLIN, a parabolic interpolation function. The calculation starts by assuming an initial value for the thermal diffusivity equal to that corresponding to the fourth input temperature. Using this value, a first approximation of the temperature at the desired location is calculated. This temperature is then compared with the initial guess (the fourth input value for the first iteration), and, if the two temperatures disagree by more than five degrees, a new value for the thermal diffusivity is calculated corresponding to a temperature halfway in between the previous two. This new value is used to re-calculate the desired temperature, resulting in a new estimate for it. The process is repeated until convergence is reached, usually in less than twenty iterations (see Figure 3.9).

The program is written in such a way that the final temperature output data is both displayed on the terminal and written on a data file for post processing.

3.3 Comparison of computer model output to experimental data

In order to evaluate the validity of the heat transfer model that was developed, it was necessary to compare the computer model output data with known experimental results. A literature search revealed that considerable data was available from flash-butt welding experiments conducted by Nippes and others.(25) The experimental work had been performed on AISI 1020 steel, and at various platen velocities and accelerations. Because of the availability of this data, it was decided to duplicate the experimental conditions within the model as best as possible, and to evaluate the accuracy of the output.



* Is present
temperature
more than
five degrees
above previous
temperature.

FIGURE 3.9: Subroutine Flow Chart

Computer runs were thus made using the following conditions:

Flashing velocities: 0.074/0.144/0.326 (in./sec)

Flashing accelerations: .004/.01/.02/.04/.1/.9 (in./sec^2)

Instantaneous distance from interface: .05-.45 (in.)

Temperature range: 80 - 2750 (deg. F)

The model also required information as to the size of the time step over which the integration would be conducted, as well as the end time to be considered. The end time value was obtained by using the equations of motion for a particle subjected to constant velocity, or acceleration, and then solving for time at a selected burn-off distance. By following this procedure, an experimental data point could be selected and the computer model could be run for the appropriate time.

Since the program allows for the independent selection of the integration time step by the user, it was important to determine what requirements or limitations were associated with this variable. Too large a time step could result in inaccurate temperature values, whereas too small of a step would lead to inefficient utilization of computer time. Several test runs were conducted on the constant velocity model by varying the time step while holding velocity, total time, material properties, and initial temperature constant. No significant changes in the temperature output readings were observed once the time step was assigned a value less than 0.05 seconds (see Table 3.1).

Similar test runs with the constant acceleration model were not as conclusive, since the temperature output appeared to oscillate throughout the range of time-steps investigated. As a check, the temperature range was varied, and the temperature output began to stabilize. Within the normal flash-butt anchor chain welding temperature range (1550-2750°F), an integration time-step of less than .05 seconds again achieved consistent readings. Based on these two results, a decision was made to conduct all test runs at a time-step of .01 seconds to ensure adequate integration accuracy.

Since the normal temperatures profile during flash welding shows such a steep rise during the early stages of burn-off, some difficulty was anticipated in trying to correlate the model output and experimental data within this range. Since a small error in time selection could cause a considerable error in the temperature output, and because of the lack of actual data points in this area, it was decided to first test the model at a later stage of flashing. Savage(25) had concluded from his experiments on constantly accelerated platen motion that a fairly stable temperature distribution was established in the weld specimen after a burn-off of about 0.45 inches was accomplished. For this reason, the computer model was run at the appropriate times for the selected velocities and accelerations, to correspond to a burn-off of 0.45 inches.

TABLE 3.1

EFFECT OF INTEGRATION TIME-STEP

Integration Time-Step	Temperatures at Instantaneous Distance From Interface (in.)				
(sec.)	.05	.15	.25	.35	.45
.01	2209	1564	1164	886	680
.025	2210	1564	1164	886	680
.05	2206	1561	1162	884	678
.10	2179	1536	1118	886	681
.25	2294	1399	1090	835	648
.50	2191	1464	1107	851	664
1.0	1942	1350	1081	840	656

V = .074

Sample runs were first conducted by running the constant velocity computer model. The temperature values obtained from these runs were considerably lower than those obtained from experimental work. Since these calculations had been performed assuming a constant thermal diffusivity, it was decided to determine the influence that changes in diffusivity had upon the output temperature. Various values of thermal diffusivity were run, and the results indicated that the use of an average value would not result in accurate output data. Because of these observations, the main program was modified to accept ten values of thermal diffusivity and interpolate for the correct value based on the calculated temperature.(24) Test runs with these modifications resulted in closer correlation between the model and given data, but sizeable differences still existed, especially at the larger instantaneous distances from the moving interface.

Further test runs revealed that the calculated values of temperature were strongly influenced by the value of parameter FINAL, the total time interval from the start of flashing for which temperature calculations were desired. In all previous computer runs, calculations were always performed until the FINAL time, with temperatures for intermediate time instances been read from the resulting output file. However, when comparing these intermediate values were always lower than the others (composite time curve in Figure 3.11). As a consequence of this observation, the mathematical model was re-examined. It was revealed that the latter approach was the correct one. Physically this also makes sense since the model has an inherently faster temperature growth rate towards the end of the integration time period, so that at any intermediate time steps the true temperature profile within the specimen is under predicted. Based on the above facts, it was concluded that in order to realistically compare the model to Savage's data, a separate computer run would have to be conducted for each data point using the respective burn-off time as the integration end-point (FINAL).

Test runs were conducted at three constant velocities (.074, .144, .326 in./sec), and in each case, five instantaneous distances from the interface were studied. These model outputs were compared with the experimental data, and a sample comparison of the resulting temperature profiles appears in Figure 3.12. As can be seen from the figure, the proper trends are followed by the model, but the actual temperature readings differ by varying degrees of accuracy. The curves are in closest agreement with shorter instantaneous distances and intermediate velocities. From these outputs, it can be concluded that the model, in concurrence with experimental data, exhibits the following trends:

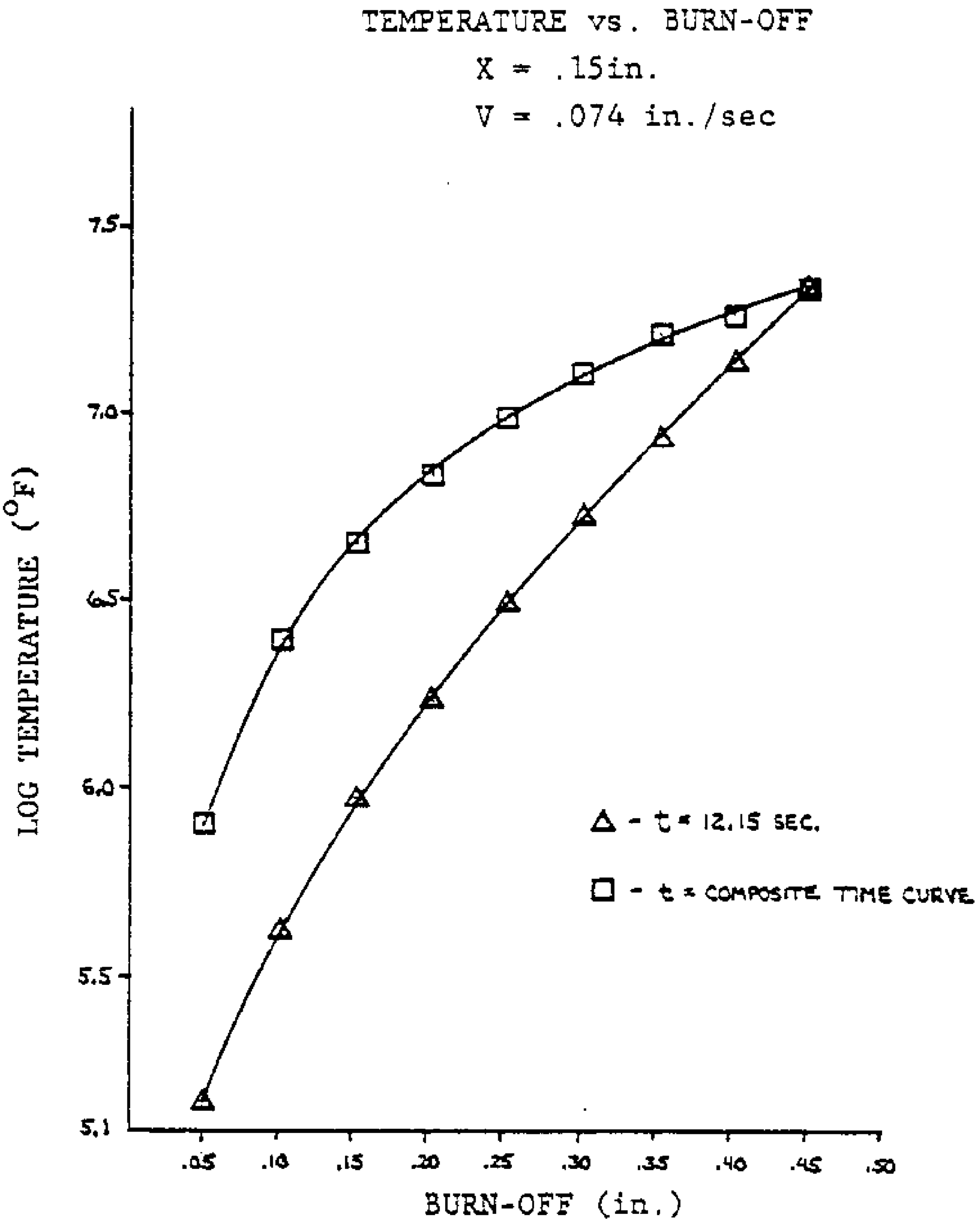


FIGURE 3.11: Effect of Final Time on Temperature Values

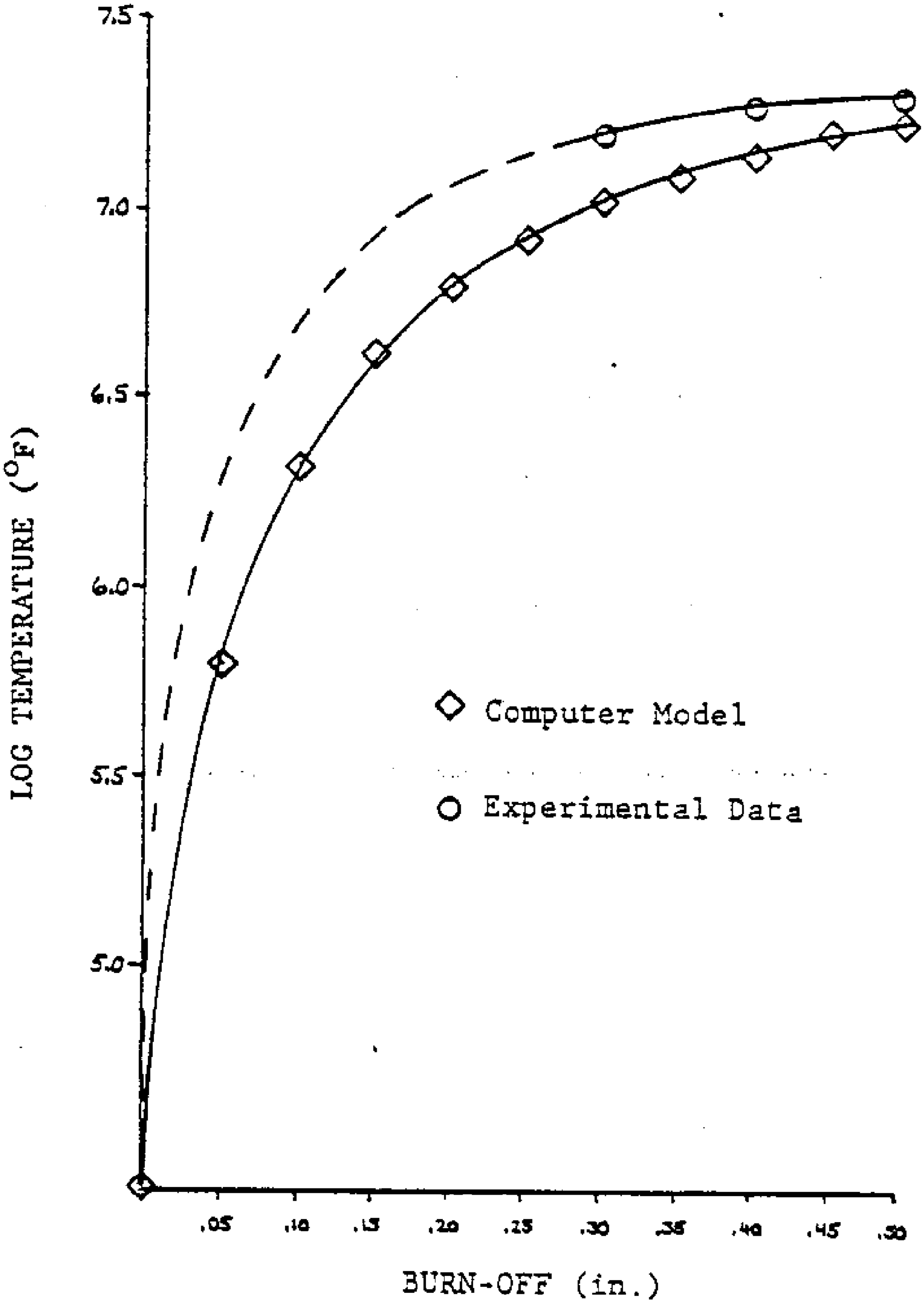


FIGURE 3.12: Correlation of Model Output to Experimental Data

1) As the velocity of the platen increases, the temperature profile decreases at each specific point.

2) As the instantaneous distance from the interface increases, the stable temperature profile decreases.

One inconsistency that exists in the linear model is the fact that at very small distances from the interface (i.e., less than .05 in.), temperature fluctuations occur which indicate that the model may not be applicable to the area close to the interface. Possibly at these small distances the planar heat source model is inadequate to account for the arcing that occurs at the interface after metal expulsion, as well as for any additional heat input that may come from the surrounding activity.

The experience gained from the trial runs of the linear model was used to modify the parabolic flashing pattern model prior to conducting any trial runs. Once these alterations were made to the programs, data runs were conducted at the earlier specified constant accelerations. The output from these runs, which were calculated over a temperature range of 80-2750 (deg F.), showed little correlation to the experimental temperature values. The calculated temperature values followed the opposite trend of experimental data in that as the value of constant acceleration increased, so did the temperature of the specimen. In addition, the model generated temperatures which were too low at some burn-off's, and sometimes too high at other burn-off's. Because of this tendency, and also due to the fact that the parabolic math model was more sensitive to the integration time-step, additional tests were run with various time steps to check the model response. Time steps down to .001 second were utilized, but no conclusive results were obtained. One point that was established from the testing was that just as with the linear case, the model could not hold up for points too close to the interface. For this reason, the values at a distance of .05 inches were discounted as being invalid.

By neglecting the very short distances from the interface, a more favorable pattern could be seen in the temperature profile with increasing acceleration. Table 3.2 shows that at very low accelerations the improper temperature trend was exhibited at a further distance from the flashing interface. As the acceleration increased, more and more of the calculated temperature followed the correct trend. Even with the proper trend developing, the temperature values were not agreeing with the experimental data. To check to see if the fault was with the model not being appropriate for large burn-off, several additional runs were made at very low burn-off (.00625 - .025 inches). The results from these data collection runs revealed a similar

TABLE 3.2

EFFECT OF ACCELERATION ON TEMPERATURE DISTRIBUTION

CONSTANT ACCELERATION (in./sec^2)	TEMPERATURE AT VARIOUS INTERFACE DISTANCES (in.)				
	.05	.15	.25	.35	.45
.004	2750	2280	1981	1820	1722
.01	2750	2172	1859	1718	1635
.02	2750	2033	1764	1641	1586
.04	2725	1882	1666	1585	1559
.1	2450	1712	1578	1553	1551

trend which indicated that the temperature calculation was more strongly influenced by the acceleration than the burn-off.

As another check on the parabolic model, an average velocity was calculated internal to the program, based on the input acceleration and final time. This average velocity was used to calculate the temperature rise, and results similar to those obtained by the previous acceleration calculations were obtained. This further indicated that the model was strongly driven by the platen acceleration. It was also noted that very small changes in the upper integration time could cause large changes in the temperature output. As an example, the parabolic model in one case gave a temperature difference of almost 200 degrees for an increase in final time of .05 seconds. Because of the numerical sensitivity of the model, it appeared that consistent results might be difficult to obtain.

Instead of attempting to match existing data, it was decided to investigate the model response to the temperature range of the flash welding process. Assuming a bar stock preheat of 1550°F, the parabolic model was run in this range, and the results appeared quite reasonable. Because the proper trends were present in this case, the temperature rise, to which the metal is subjected, must also strongly influence the temperature profile. Running both the linear and parabolic models within the chain fabrication temperature range gave reasonable results, since the trends that resulted were in agreement with Nippes' work, (see Figure 3.13). It was not possible to evaluate the accuracy of these calculations since no experimental data existed for these temperature ranges.

Conclusions

The heat flow model was developed upon the basis that all the heat transferred to the bar stock during flashing was accomplished by conduction. From this point it was assumed that the heat source could be modeled as a quasi-stationary planar heat source moving at either constant velocity or acceleration. As has been exhibited by the output from the many sample runs of this computer model, the actual heat transfer process is much more complicated. The present model over simplifies the conditions, and is very vulnerable to problems generated by the numerics within the model.

Wide variations in temperature can be obtained by changing time-steps, final time, the specimen temperature rise, and other parameters. Within a specific temperature range (1550°- 2750°F.) both models appear to give fairly stable output, but at other ranges the model (especially the parabolic flashing) falls short in data correlation. The linear model shows the best agreement, but this is

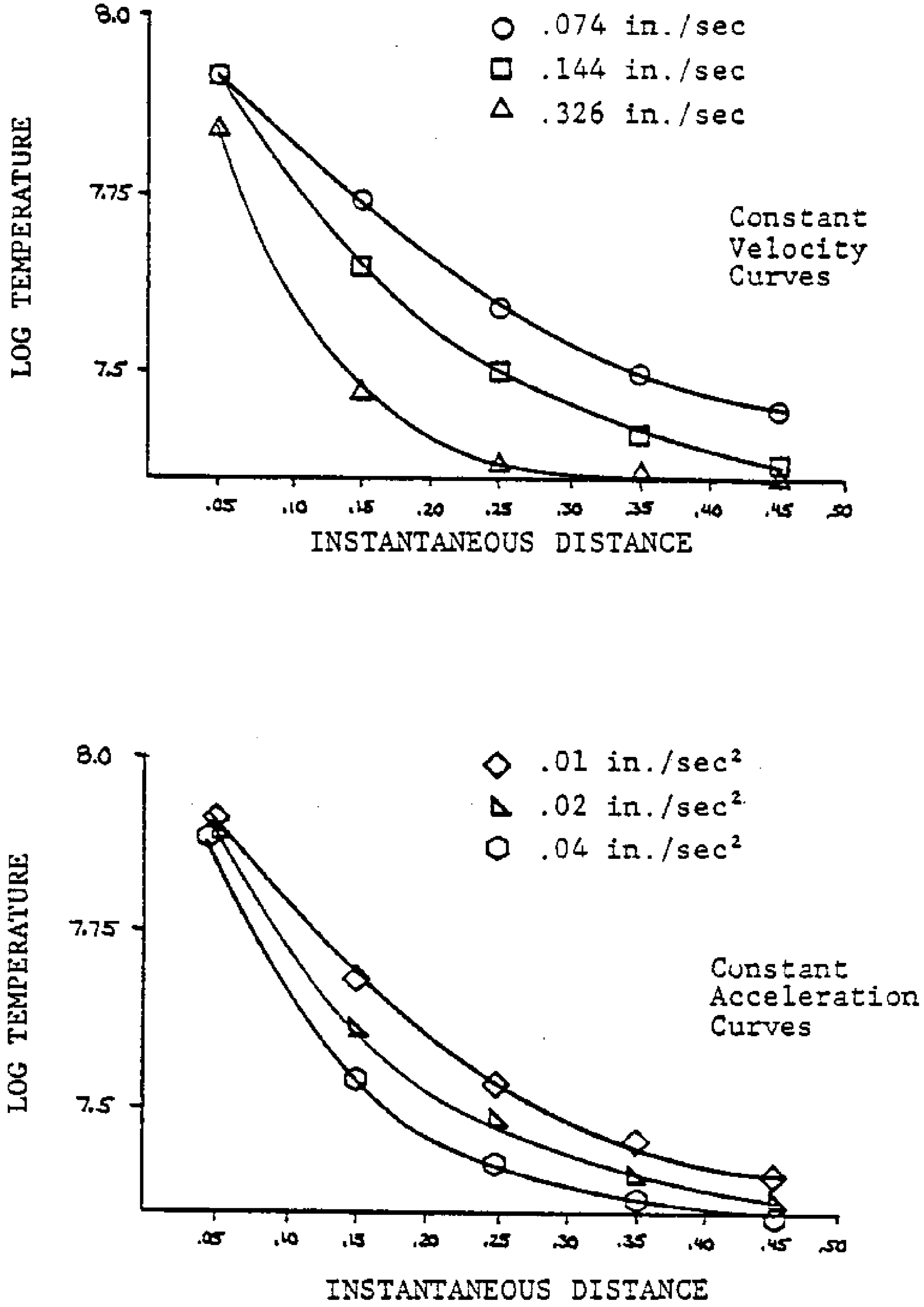


FIGURE 3.13: Model Output for Temperature
Range 1550 - 2750°F at .45 in. Burn-Off

limited to intermediate distances from the flashing interface. At distances greater than about .25 inches the model exhibits a rapid temperature decay which disagrees with established data.

One of the difficulties in matching the experimental data is the complexities of the early stages of flashing. The experimental parabolic flashing is not truly parabolic since initially the motion is constant velocity to initiate flashing. These complexities add to the difficulty in trying to model the interface conditions. Another problem with the model is that the parabolic motion cannot be accurately modeled by a quasi-stationary heat source. Since the heat flow is so rapidly changing with the accelerated motion, the model cannot adequately develop the proper temperature growth rate which occurs under real conditions. For these reasons, the present model has limited use, in a restricted temperature range.

A much more complicated model could be developed, one that may consider the individual point heat sources that randomly appear over the surface during flashing. A model of this type would entail extensive effort and even then the value of its results may prove questionable. In the flashing process. there are so many variables that even a very involved model may still give unsatisfactory results when compared to experimental values. Slight inconsistencies in the material properties or welding input variables could drastically change the real life output from the anticipated model values.

In conclusion, there appears to be little advantage in developing a detailed model of the flashing process since no matter how detailed it becomes, its output will not exactly match the experimental data. Secondly, the amount of effort that would have to be dedicated to a project of this magnitude could possibly be better invested in the development and implementation of sensing and monitoring devices to better control the process. The main objective is to develop a quality product, and this could be better achieved through improved production and quality assurance, than through system model development.

4. Strategies for In-Process Sensing and Control

4.1 The need for sensing and control

The factors affecting flash welded anchor chain were identified earlier in Chapter 2. In order to produce a sound, reliable weld, these parameters must be adequately controlled so as to keep them within the established acceptable ranges for the various sizes and types of steel chain produced. Currently chain production is accomplished either by means of a very labor intensive, semi-automatic welding process (i.e., carrousel station set-up), or by means of more modern automated flash welding machines. The present trend is towards the development of more completely automated manufacturing equipment centers and robotics, which will require more complicated control and sensing systems. Economic, technical and social factors have been responsible for the trend, and a list of some of the specific reasons follows:(27)

Economic:

- Lack of adequately trained and skilled personnel
- Inefficient use of labor force during equipment change outs and short production runs
- Reduction of labor intensive fabrication methods

Social

- * Reduction of monotonous, tedious work tasks
- * Elimination of noisy, unhealthy, stressful working conditions
- * Easier control of environmental conditions

Technical

- * Adherence to stricter safety standards
- * Improved product quality due to reduction in manufacturing errors
- * Greater standardization of output by elimination of human subjectivity during production process
- * Reduction in time required for measurements and other tasks.

The overall objective of this increased automation is to reduce the non-productive time of the work cycle (Figure 4.1), and hence increase the overall system productivity. With advances in the field of sensor technology, considerable gains should be able to be accomplished in reducing the operating time of the newer programmable manipulation devices.

Of the machines that are in operation today, the majority of them are more programmable than automatic in

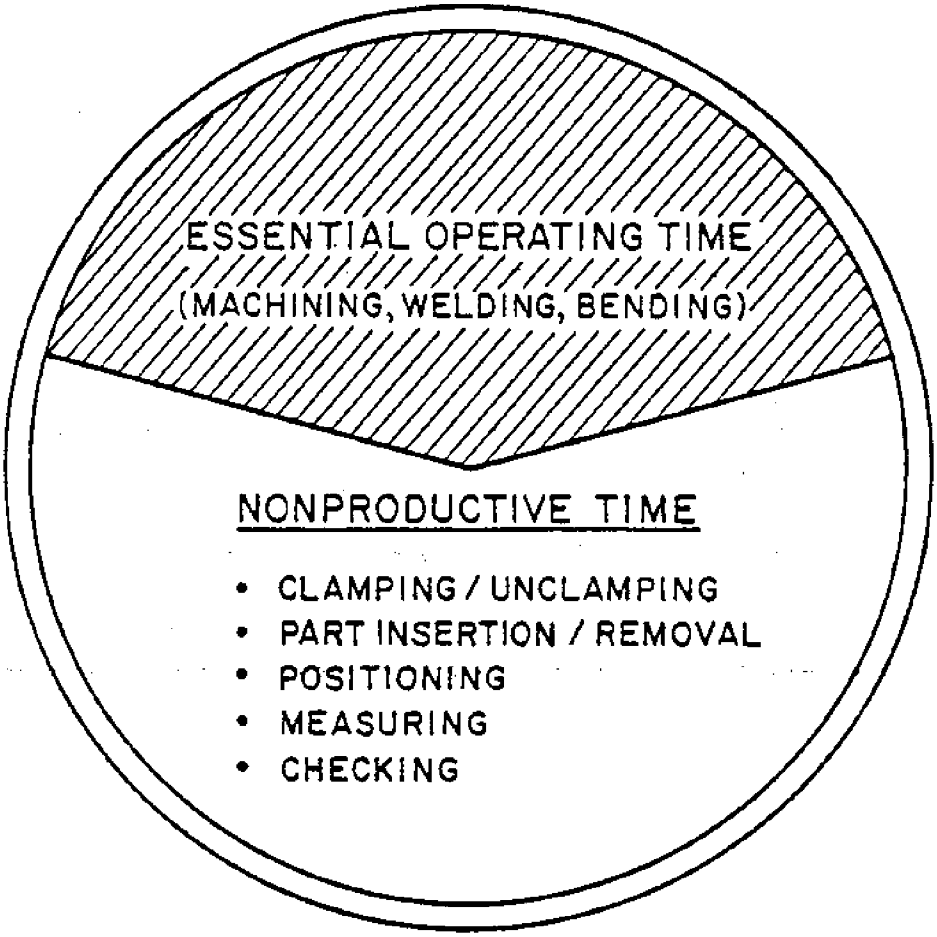


FIGURE 4.1 Typical automated production work cycle

nature, since they can only reproduce the welding parameters which have been programmed into the machine. Optimum welding conditions have been determined in advance, from past practice and experimentation, and these values are used as the program inputs. Once a welding operation is started, it is performed by following the predetermined program. Very few, if any, of these parameters and procedures are actually monitored and sensed during the welding operation and chain manufacture. Since there is no "feedback" to the machine, no self-compensation can be made to make allowances for certain peculiarities that may exist in the particular piece being welded. Due to this system inflexibility, every chain link is welded under the same input parameters which assume ideal conditions. Slight variations in certain parameters of the bar stock (i.e., cleanliness of the bar stock abutting surfaces) can cause the resultant weld to exhibit varying quality from link to link. As a result of the lack of adaptive controls on these machines, their reliability is degraded and will vary with the type of material being welded.

On many machines the only adjustments that occur are the initial zeroing out of the welding machine prior to setting in the welding parameters for the new production run. Even under these limited adjustment and control conditions, fairly good welds can be achieved during normal operating conditions. Depending upon the type of machine being used, and the conditions of the bar stock being welded, the weld reliability can be quite high (i.e., 90%+). In many other manufacturing processes this might be an acceptable reliability, because individual parts are produced and inspected for quality before being assembled. Since the chain links are not tested until usually a shot of chain is produced, a faulty link results in chain disassembly for link replacement which interrupts the normal production cycle. This results in higher costs in chain production, lost time, and materials handling problems at the welding machine, since the entire length must be transported to be repaired. When we are dealing with anchor chain, we are primarily concerned with several aspects:

1) Chain integrity and strength
2) Fabrication cost
3) Production time
4) Quality control

All of the aforementioned can be linked directly with the process reliability. A very high reliability must be achieved in the welding process and this same quality must also be reflected in the post welding phases; flash removal, stud insertion, stud welding, heat treating, and inspection.

Presently, industrial and research organizations are very interested in developing higher reliability, in many types of automated fabrication, through the utilization of state-of-the-art electronics. In recent years, the lack of suitable measuring procedures and systems has increasingly placed a restraint on the development of automation. One of the major obstacles has been the machine's inability to duplicate the human sensory faculties, and hence, the "automated" systems have still been forced to involve human intervention at certain stages of the operation. The human faculty of vision is unsurpassed when it comes to recognizing tasks, such as visual inspection.(27) This is but one example of a measuring system, which is generally categorized as pattern recognition, others being measurement of sound and touch. Pattern recognition requires more than determination of measurement values; it requires decision making, and, therefore, some type of intelligence. These "intelligent" measuring systems represent the most recent developments of measuring technology and hold much promise for the future. Since the objective of all manufacturing systems is to produce high quality items in desired quantities, it will remain the task for the upcoming measuring technologies to provide the information necessary for optimizing the production process. This information will have to be fed back continuously to the manufacturing equipment to guarantee quality products.(28) The basic principles of optical, acoustic and tactile transducers will be studied and the possibilities and limitations of intelligent sensor systems for anchor chain fabrication will be reviewed.

4.2 Types of sensor and control equipment available

A relatively new field of industrial measuring technology has developed in recent years, which deals with the overall measuring process during an industrial operation. As described by Hart(28), the industrial measurement process can be broken down into two types of operation; continuous and discontinuous. The continuous operations, which usually deal with process measuring techniques, such as process analysis and control, are relatively simple to handle. Input values are given to the equipment and then these values are monitored and adjusted throughout the process to keep them at their pre-programmed levels. This area of measurement techniques is quite well established, and most present-day automated welding equipment utilize these methods to control the input welding parameters. The major shortcomings in measurement technology occur during the discontinuous production measurement phase, where tasks such as quality assurance and production control are required to be performed. These tasks are very demanding, and in many cases they require optical, tactile and acoustic sensing. Over the years, engineers have equipped automatic welding machines with rudimentary sensing capability to replace human faculties. Many of these techniques are still in their early stages of development, and it is in this area that the problems arise in measurement technology.

There are many types of sensors and controls under development, and in use today, which are attempting to deal with these more complicated task requirements. Since the measuring variable they are trying to determine cannot always be described by a physical unit, or the result expressed as a single number (such as in quality acceptance standards), the task becomes quite complicated. In order to arrive at the desired result, both an information processing and discrimination phase are necessary which, therefore, require an intelligent measuring system.(27) The system will require the capability to decide between different alternative it can take during a production sequence. This sytem capacity to alter the manufacturing cycle, based on feedback information, requires that there be a large amount of accurate information available on the instantaneous values of the process parameters. A system of this type requires sensors which can obtain information from the chain manufacturing environment and relay this data to a processing stage which can, in turn, make adjustments to the manufacturing sequence by means of a closed feedback loop (see Figure 4-2).

Even within the sensory tasks there are different degrees of complexity with which we can deal. The simpler sensors may only be required to perform binary decisions, such as yes/no or on/off. A more complicated sensor may have to measure part size, and an even more complex sensor

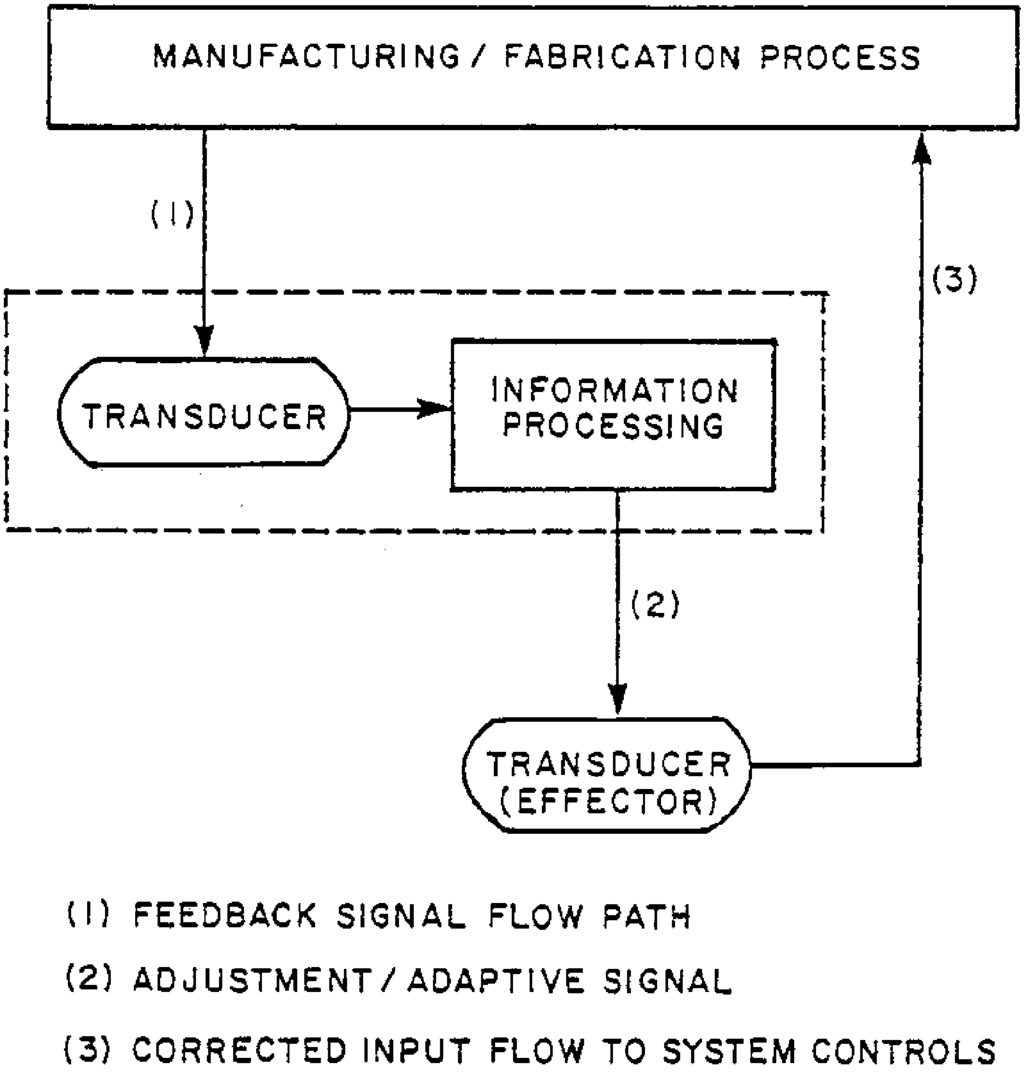


FIGURE 4.2 Automation of an industrial process

would be required to perform tasks of pattern recognition. As is the case with most automated manufacturing processes, the sensor tasks required during the flash welding phase mainly occur during the chain and link manipulation and movement. In a completely automated chain production process various types of sensors would be needed to monitor the entire process, ranging from the simplest to some of the most complex in nature. The various types of sensors will be examined to see how they may be adapted to the task at hand.

4.2.1 Optical transducers. Of all man's senses, his vision tends to be the most useful where measuring technology is concerned. The degree of optic resolution exceeds his tactile senses by an order of magnitude, and far exceeds his audio sensing capabilities.(27) For this reason, the trend in modern sensor development has been to favor optical and image sensing methods in the hopes of achieving the accuracies needed for the control systems. Many kinds of optical sensors have been developed and are being utilized in various industrial processes. Some of the most important tasks of an optical sensor are:to determine the position of a workpiece, marking, measuring and tracking. These sensors include optic fibers, lasers, television and other optical imaging systems. The laser and optic fiber sensors are readily adaptable to measuring and alignment tasks, which they can perform quite quickly and with great accuracy. These sensors could accomplish several measuring tasks which could be required during the chain fabrication process to ensure that chain quality and specifications are met. Some examples include, but would not be limited to, the following:

1) Bar stock link length (unbent)
2) Bar stock link length (unbent, preheated)
3) Upset distance
4) Abutting surface alignment
5) Stud length
6) Chain length over a specified number of links

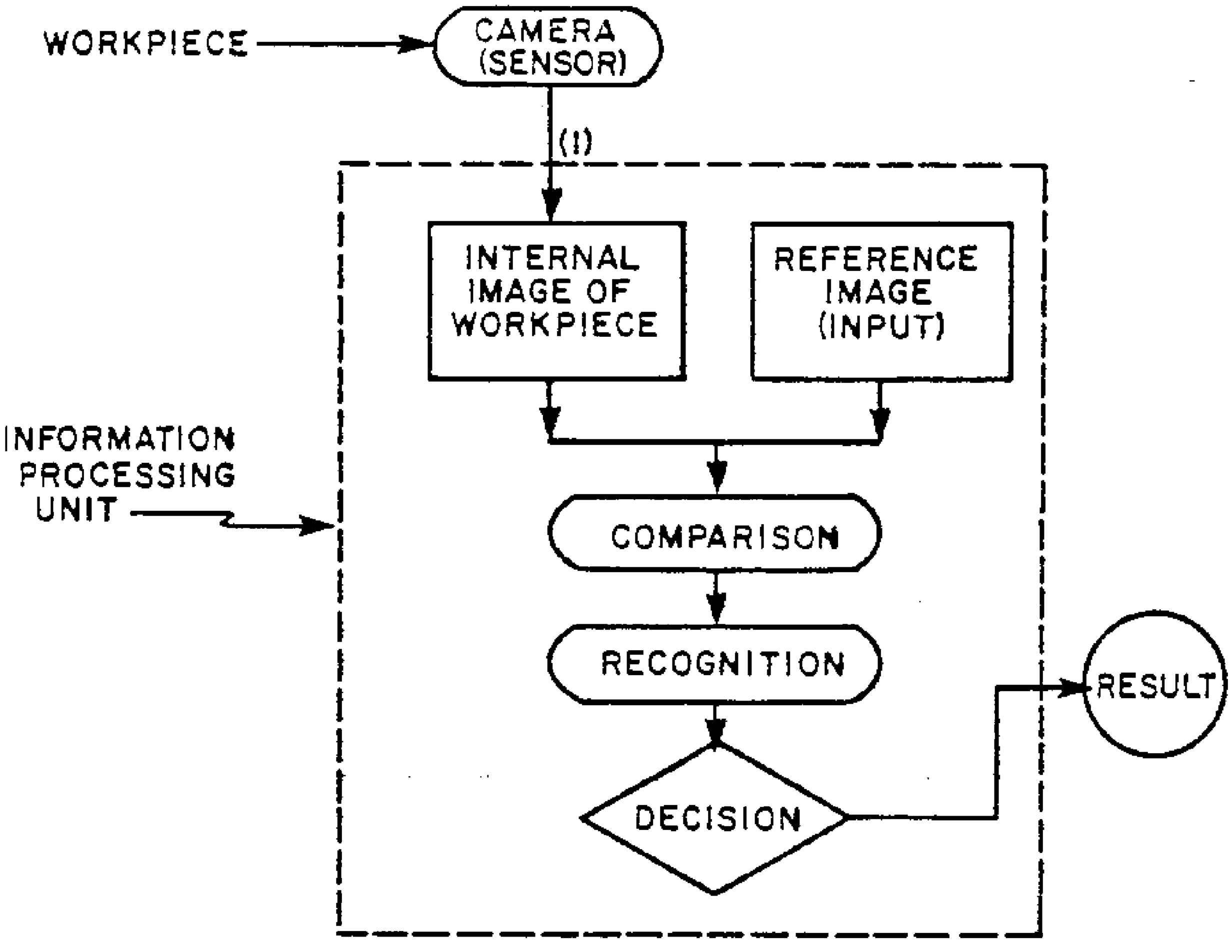
Many other measurements could also be obtained by optical sensors, but some limitations on their application can be imposed by the working environment.

Optical sensors have a tendency of working very well in a controlled laboratory setting, but their usefulness deteriorates very quickly when they are placed in a hostile work environment. The more complex the sensing system, the greater the degredation caused by the actual working conditions. This has proven to be one of the major obstacles in the implementation of these techniques into industrial production methods. Welding environments demand a lot from sensors, since these instruments must face smoke, dirt, electrical interference, continuous usage, radiation, heat, and operator mistreatment. Even well-built sensors must be prudently maintained and properly located to ensure that adequate performance can be obtained. Hence, many users prefer sensors that do not contact the workpiece since this offers the advantage of covering a wider area of sensing resolution than can be obtained from a single-point contact.(29) Another benefit of the non-contacting sensors, such as optic, is that the instrument is subjected to less mechanical misalignment, damage and wear.

4.2.2 Optical image processing. Even with all of these obstacles, many achievements have been made in the uses of the more complex sensors. The main task of the image sensor element is to convert a three-dimensional optical picture into a time sequence of electrical signals which can be understood by the control system. The image sensing equipment is very important since it is the direct link between the industrial operation that is being performed and the information processing system. The most commonly used sensors of this type are various kinds of television cameras. The distinction between the different types is based upon the kind of sensing element that is employed. Different sensor elements such as Sb_2S_3, PbO, and Si, are suitable for different detection tasks. These elements also allow for a wide range of conditions within which these cameras can be effectively utilized. In a visual sensing system, it is usually critical to establish suitable lighting conditions in order to clearly define the light and dark areas which will simplify the recognition process.(30)

Once the camera or other appropriate sensor has picked up the image, the system must process this information so it can be used in pattern recognition. The process entails comparing the presented pattern, at the industrial process, with a known acceptable pattern which has been stored in the system's memory. This image must be converted by the sensing element to analogue video signals and then to continuous digital signals (A/D conversion), which can be used by the system's picture processor. The processed information is then passed to the mini-computer for comparison and recognition. The key to a successful system is therefore the ability to establish good reference patterns in the memory bank, which can be readily accessed during the manufacturing process. The easier it is for the system to learn reference patterns, the more flexible the system becomes in being able to more quickly adjust to changing requirements. In industrial production there are many tasks where the recognition system must adapt itself very rapidly and at low cost to changes that are imposed. Such would be the case in welded chain manufacturing where the image being compared could range from the acceptable dimensions of the finished link to the comparison of the actual flashing action to the stored "ideal" conditions. All of these image sensors require considerable memory storage and, therefore, dictate the use of microprocessors and computers with sizable memory capabilities, (see Figure 4.3).

One of the more complicated aspects of image sensing and processing is the creation of a reference image that is adequately described to allow for proper recognition characteristics. The user fixes the object, or specific features, in the system memory by describing it in as detailed a manner as possible. Sometimes several views of the object are required to completely define the image. In some processes the reference pattern can be more easily established by tracing along an actual drawing of the component (such as is done in CAD/CAM applications) and having this data read into memory to be used as a data baseline. Where the object being viewed merely has to meet some minimum or maximum dimensions, and it is fairly simple in design, another method of recognition can be used. In these cases, a method of masking can be used, whereby the optical sensor can detect if the component dimensions lie outside the acceptable limits (see Figure 4.4). This is usually accomplished by providing a photographic film overlay to the optical sensor, which establishes the acceptable/unacceptable ranges or dimensions.(27) A masking method is usually quite good for repetitive production, but it is not readily adaptable to small lot/varying size production runs. With any of these techniques, once the data base has been



(1) DATA CONVERSION TO FORMAT SUITABLE FOR INFORMATION PROCESSING UNIT

FIGURE 4.3 Image sensing and processing

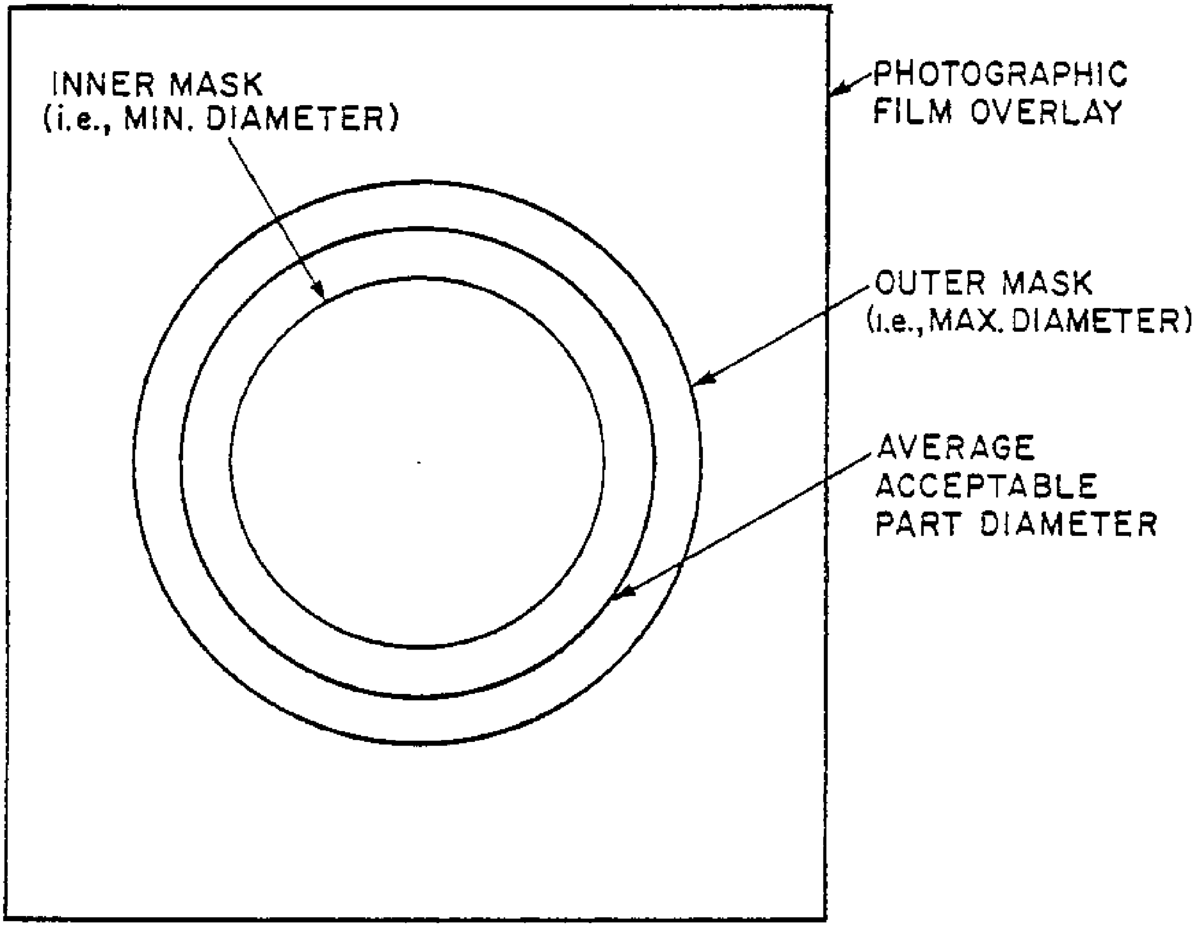


FIGURE 4.4 Illustration of optical masking method for image sensing devices (27)

input and favorable results have been obtained, this sensing system can be integrated into the manufacturing process.

Optical image sensors can also be used to perform tasks other than part measurement, placement, sizing, and shape distinction. Possibilities exist to utilize these optical techniques to perform other tasks such as:

1) <u>Temperature measurements</u> - by recognition of the actual color, or the infra-red signal that is generated.

2) <u>Stress measurements</u> - by using the imaging techniques in conjunction with moiré photography to study welds at high temperatures (strain distribution).(31 and 33) Another means of high temperature thermal strain measurement is through the use of laser speckles.(33)

3) <u>NDE of magnetic particle and dye penetrant tests</u> - by comparing the optical image of the tested parts surface to established acceptance/rejection criteria. Through pattern recognition, flaw concentration measurements, and critical flaw length data, the parts' quality could be evaluated during the on-line process.

These are only a few of the many areas where these optical sensors could be of use in an automated chain production system.

4.2.3 Acoustic sensors and signal processing. Acoustic sensors are presently less commonly used during the industrial process because of their lower reliability and accuracy when compared to the optical and tactile sensors available. These sensors tend to be more difficult and costly to develop since acoustic sensing and signal processing is quite a complex and relatively young technology. Acoustic sensors are more prominent in quality and non-destructive testing (NDT) procedures, where the environment can be more stringently controlled. Most of the acoustic testing procedures use airborne and structure-borne sound signals in an attempt to draw conclusions about a system's production quality.(29) Similar techniques have been used in evaluating the operating conditions of machines and manufactured products. The latter procedure requires that an acoustic data baseline exist for comparison purposes. Two methods of acoustic testing exist, active and passive. The passive methods are based on the analysis of the equipments self-generated noise, whereas the active method studies the oscillation behavior of the component due to an externally induced sound signal.

Most NDT methods are intended to detect internal flaws that are likely to cause fatigue or static load failure.

These tests are performed on work in progress so that defective parts can be rejected early, thus saving additional expenditure of money and effort. The tests can also be performed on used components during disassembly of equipment which has been in service, in an attempt to detect the start of fatigue cracks. To date, success in flaw detection has been achieved in the following areas:

- Production faults
- Excessive noise production
- Damage to subassembly components
- Operational faults
- Discontinuities in materials

Some of these successful tests have been adopted to the industrial environment, but others have only had limited application outside the laboratory. As is the case with all sensors, the work environment of a welding, fabrication facility places a tremendous strain on the sensor's capabilities, and considerably degrades their reliability. One major impact on acoustic sensors has been the high ambient noise level that is present in industrial activities. These conditions require that extensive noise filtering and sound isolation requirements be imposed if the sensors are to be able to perform properly. Because of these difficulties and accuracy limitations, rapid development and industrial implementation have not occured as with other types of sensors.

Ultrasonic methods of flaw detection can be used on all metallic materials. These methods rely upon the transmission and reflection of ultrasonic beams. Reflection will occur at surfaces, such as caused by cracks or voids. The sound beam is converted into an oscilloscope trace, video terminal, or graphic plot for convenience of interpretation. In transmission methods, separate transducers are used for sending and receiving, and the interposition of a defect results in abnormal absorption of the beam. In the reflection technique a single transducer is used on the speimen. The presence of a reflecting surface, other than the member's far surface, causes an intermediate peak to show on the signal trace. Ultrasonic testing (UT) techniques are useful for detecting cracks, voids, and defects both on and far below the surface. They require operator skill and care in their application and interpretation, and this is why there is a trend towards automating the procedure (NDE).(34) Various ultrasonic techniques are shown in Figures 4.5 and 4.6.

In the area of NDT, the success rate of acoustic sensors has been considered to be questionable. As mentioned earlier, discontinuities can be located in a material, such as a chain link, but the degree to which these defects can be found rests in the quality of the acoustic test equipment and the angle of incidence that exists between

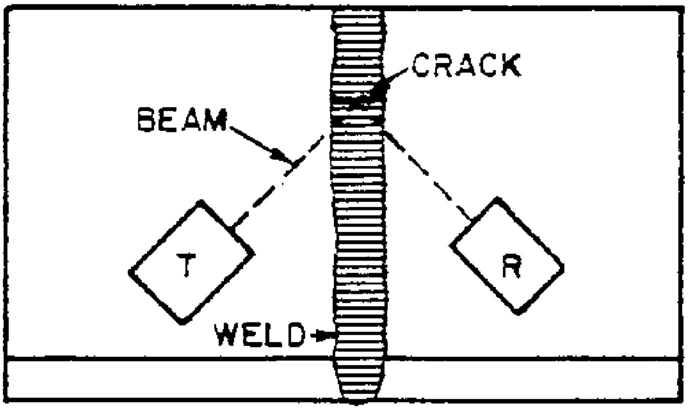


FIGURE 4.5 Transverse crack detection technique (34)

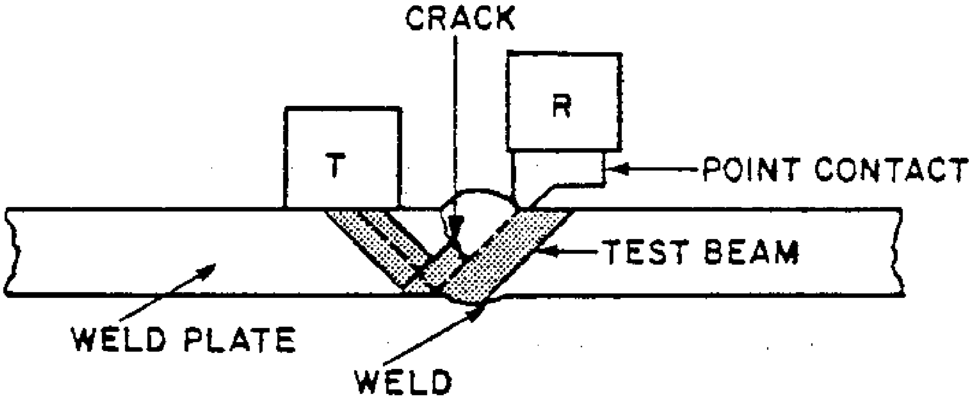


FIGURE 4.6 Manual ultrasonic techique for measuring crack depth (34)

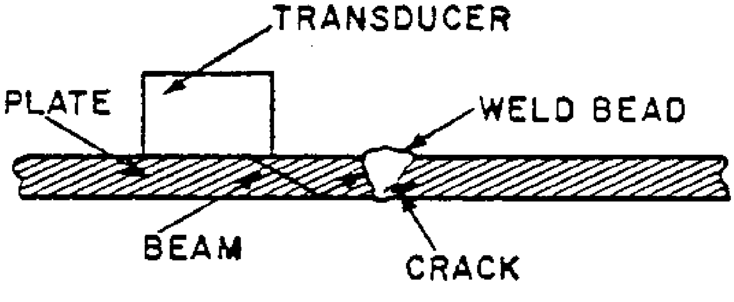


FIGURE 4.7 Shear wave crack measurement technique (34)

the transmitted sound wave and the axis of the defect. Instrument sensitivity adjustments can be made, but this can lead to erroneous fault detection. As an example, in a series of ultrasonic tests performed on samples of 4-3/4 in. flash-butt welded chain, Battelle Laboratories(8) noted that a number of defects were acoustically detected at the flash-weld area of all samples. Further microscopic investigation revealed that the majority of these flaws were the result of false ultrasonic indications. The Battelle report concluded that the use of acoustic devices for defect analysis (as they existed in 1977) was not reliable, and in general, acceptance/rejection decisions should not be based on their test results alone. Since these kinds of errors could result in the rejection of satisfactory chain and also decrease productivity, it was recommended that the UT requirement be eliminated from any specifications on welded chain, and that testing by other more reliable NDT methods be substituted.

In contrast to the Battelle report, Det norske Veritas (DNV) issued technical report No. 713525(35) on the specification for the ultrasonic examination of welds in chain links in the same year. DNV called for the utilization of the ultrasonic shear-wave technique in which the beam enters the specimen from the side at a 45-degree angle, and also requires a corresponding 45-degree transducer head (Figure 4.7). The shear-wave technique was selected because it lends itself nicely to production testing since it does not require the flash weld to be cut from the link. From these two reports it is obvious that there exists a difference in opinion on the value of UT procedures. Since both of these reports were issued, considerable gains have been made in sensor and processing capabilities.

Numerous activities have found success with UT procedures, acoustic imaging, microprocessors, and what is known as non-destructive evaluation (NDE). United States Steel Corporation, for example, test welded line pipe as it travels through the mill. Using a combination of fluoroscopic and ultrasonic examination, the welds are inspected right after they are made.(36) The fluoroscopic inspection detects slag inclusions, gas pores and other volumetric defects, whereas the ultrasonic system detects cracks, undercuts and incomplete penetration. Armco, Incorporated has successfully used ultrasonics to examine large plates used in shipbuilding and also stainless steel automobile engine valve rods.(37) The railway industry has also made great advances in ultrasonic inspection of their continuous welded rail (CWR) and long welded rail (LWR), which is produced by flash-butt welding techniques.(38) The rail industry also utilizes UT for in-service rail flaw detection.(39 and 40)

4.2.4 Ultrasonics and linear arrays. Anytime a material has to be inspected, some of the most important features required of the testing procedures are that it can be reliable, cost effective, and perform its operation at the production speed of the manufacturing system. Time cannot be wasted by testing delays, and production flow path bottlenecks cannot be tolerated. There are different ways to approach this problem; by adding more inspectors and machines to keep the flow moving, or by improving the speed and performance of the existing equipment. The latter is usually more cost effective since once a better machine is developed the annual operating cost will decrease. In the field of NDE, and in particular in the area of ultrasonic testing, one of the bigger breakthroughs in increased testing speed has been brought about by the introduction of ultrasonic linear arrays.

Lemon and Posakony(41) have shown that linear arrays can be applied in ultrasonic pulse-echo imaging because of the added speed of inspection afforded by the electronic control of the sound field. The need for multiple transducers is eliminated and by electronically switching on and off different elements in the array, a large section of material can be inspected during a single pass. Detailed information about flaws can be obtained by the array capturing the diffracted and mode converted energy from the crack. This data can be compared (by the use of a computer) to known standard flaw data which will allow for automatic characterizing and sizing of the defects.

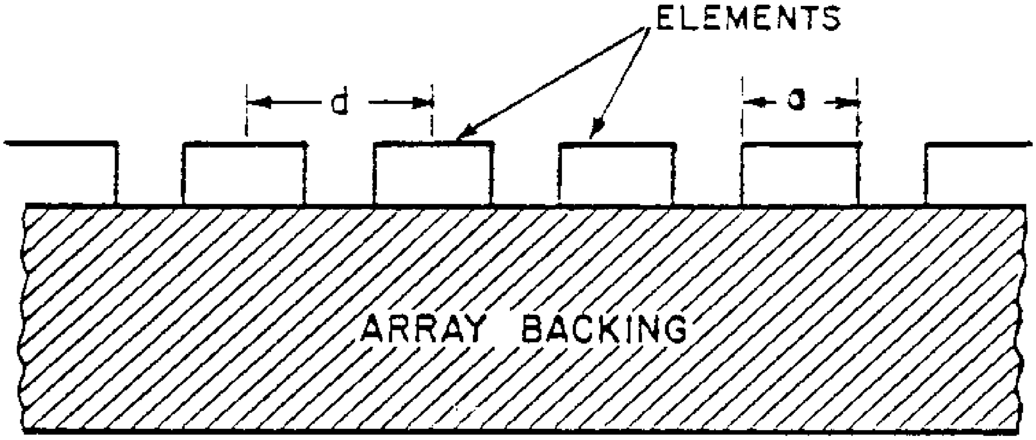
A typical linear array is shown in Figure 4.8. The key parameters are: a, the width of the element; and d, the center-to-center spacing of the respective elements. Another important requirement is maintaining adequate electrical and acoustic isolation between the array elements so that they can work independently. When we are concerned with single element sound fields (one element transmitting at a time), the width of the element is the major controlling factor in the shape of the pressure pattern that is produced. As the width parameter 'a' decreases, the angle of the pattern increases (see Figure 4.9). The equation governing the pressure pattern for a single element sound field is:

$$P(\theta) = \sin(\pi a \lambda^{-1} \sin\theta)/(\pi a \lambda^{-1} \sin\theta)$$

λ = wavelength

θ = angle at which pressure is measured

Phase steering is accomplished by sequentially pulsing the array elements and by controlling the time delay between emissions. If the time delay is set at half the period, then alternate elements will be on the same wavefront of constant phase. The performance of the array in steered and unsteered modes can be predicted and controlled by knowledge of a few design parameters. "When properly used, arrays have significant advantages and can provide



a = ELEMENT WIDTH
d = ELEMENT SPACING

FIGURE 4.8 Array design parameters

POLAR RADIATION PATTERN FROM A SINGLE ARRAY ELEMENT

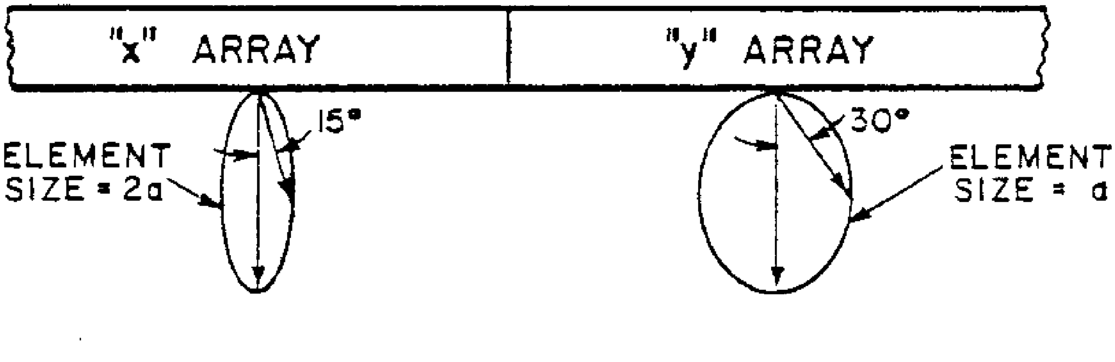


FIGURE 4.9 Effect of array element width on single element radiation pattern (41)

the means for achieving high speed inspections and other ultrasonic tests not possible with single transducer schemes."(41) By proper manipulation of sound waves, we can generate an inspection and feedback pattern adaptable to the material to be inspected. The proper selection of an array can greatly increase the amount of information we can obtain from a sample of the material. The detailed data that is revealed by the ultrasonic interrogation must be evaluated by a computer to keep it from becoming a mass of unmanageable information.

Arrays can be designed for the specific inspection task and, therefore, are adaptable to many situations. Scan speed, detail, power, and number of elements can all be varied to give the optimum type of inspection equipment suitable for the job. By interphasing these arrays with modern computer technology, man has increased the speeds at which ultrasonic data can be evaluated. The feedback data from the test specimen is compared to accepted standards and the programmed fracture mechanics theory and, if within limits, the system will accept the material. Increased inspection flexibility can be achieved by coupling these arrays with other techniques, such as signal processing to enhance the sensitivity and discrimination of signals received from the inspection system.(42) In the future, many of these methods may be combined to give more complete testing techniques, such as the acousto-optical imaging

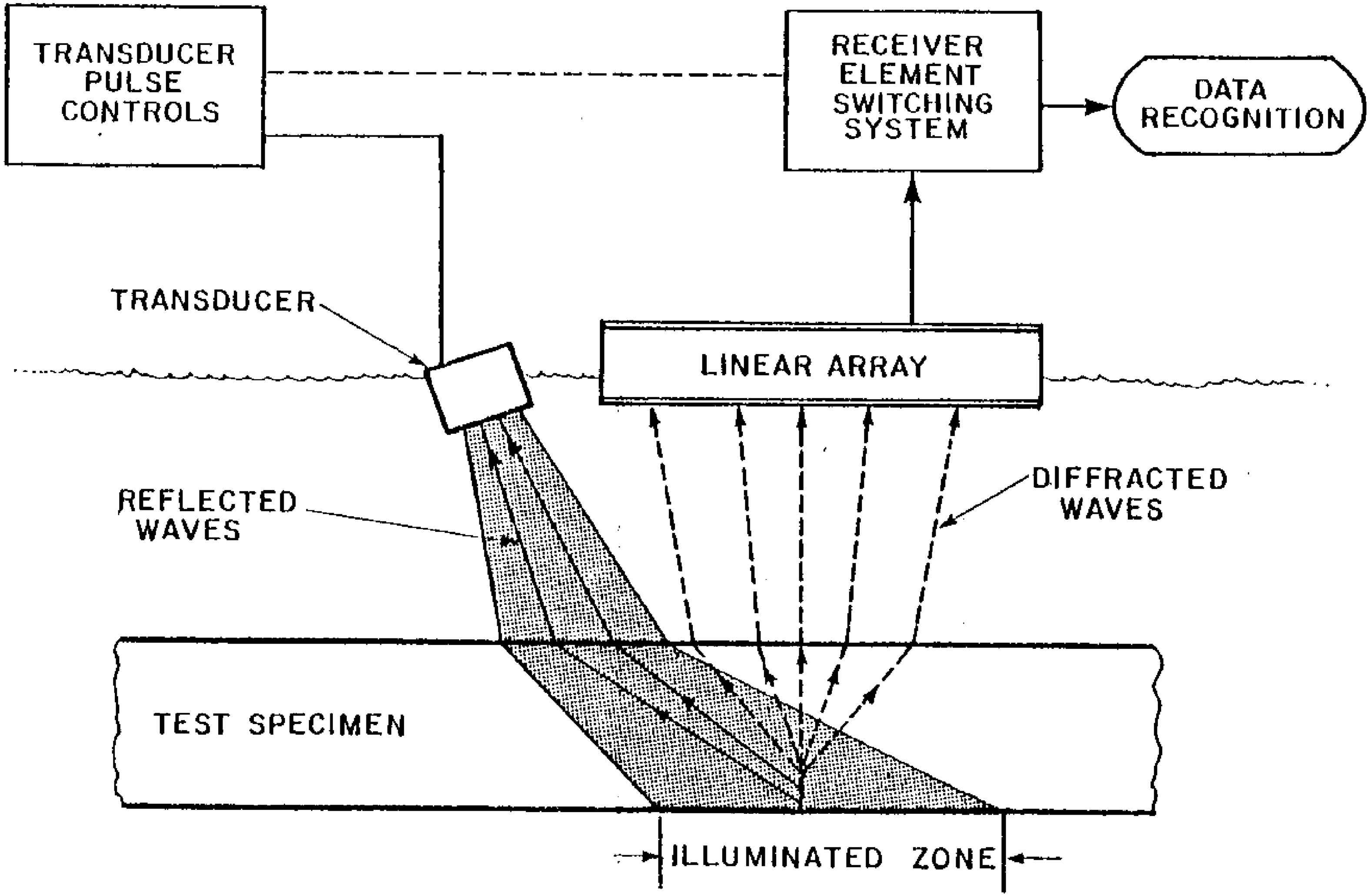


FIGURE 4.10 Use of a linear array for wide-angle flaw characterization (41)

system (Figure 4.11). This system obtains visual images of defects by using sound reflected by the defect which causes Bragg diffraction. The combination of the areas of ultrasonic transmission and acoustic emission also shows promise of yielding very successful results in the future.

4.2.5 Tactile transducers and other sensors. Some of the earliest sensing capabilities to be used on automatic welding and machining centers were in the area of tactile sensors. The early models were nothing more than mechanical guides which followed the outside edge of a plate, or rode in the weld groove, to properly locate the welding head for the required operation. With advances in controls technology, the capabilities of these sensors also improved, allowing for the sensor to follow a seam which did not have to rely on an exterior reference. By giving the sensor freedom of independent motion with respect to the welding head, more complex patterns can be followed and successfully welded.(29) Corrections for the sensor motion and time delay for the welding head are calculated and stored within the system's memory. This allows for a more accurate weld path to be followed (see Figure 4.12).

Another slightly more complex method is that of sensor programming, which entails physically tracing out the path to be followed. A needle displacement sensor follows the seam and is displaced according to the seam's direction.

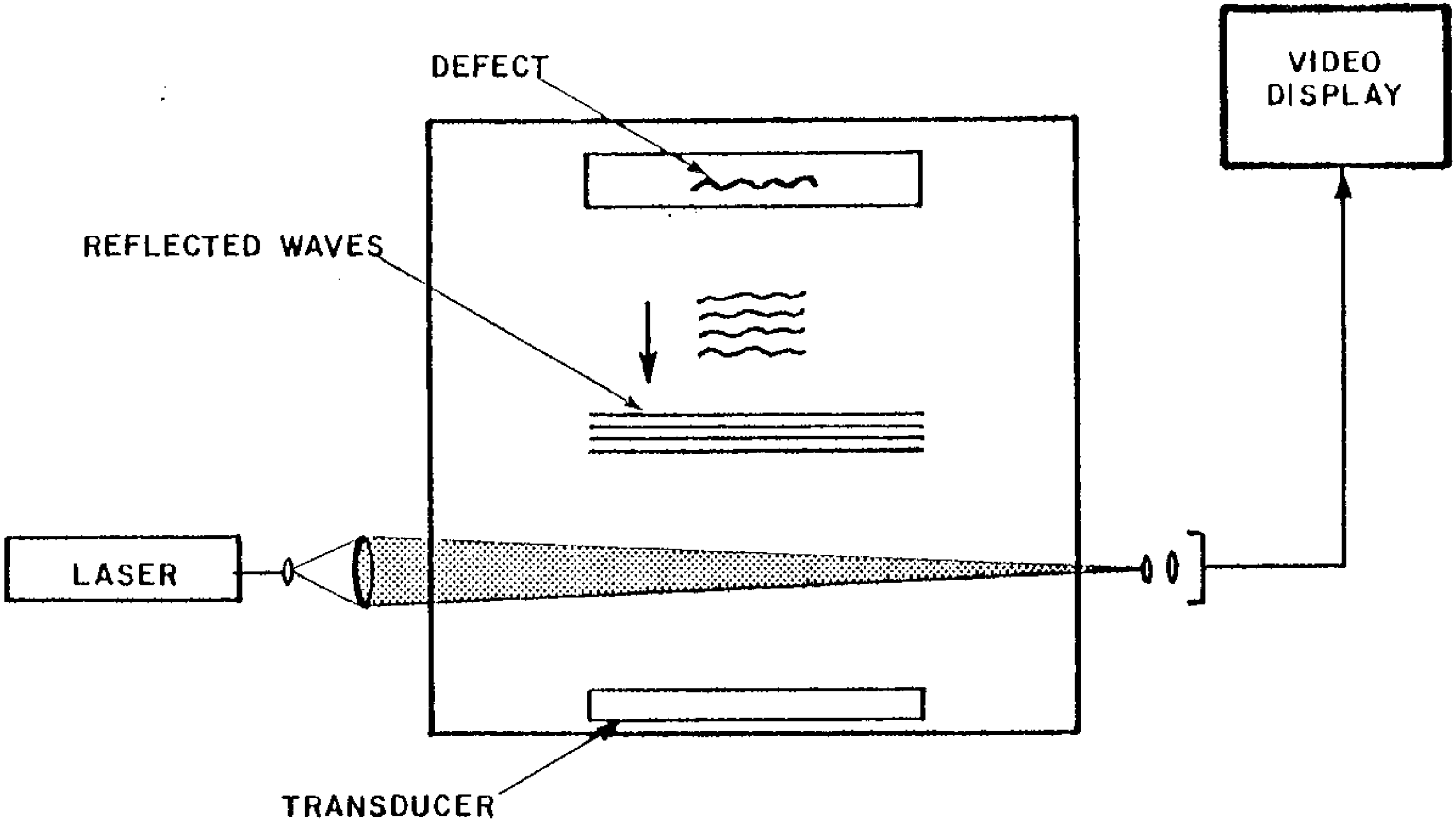


FIGURE 4.11 Acousto-optical imaging system

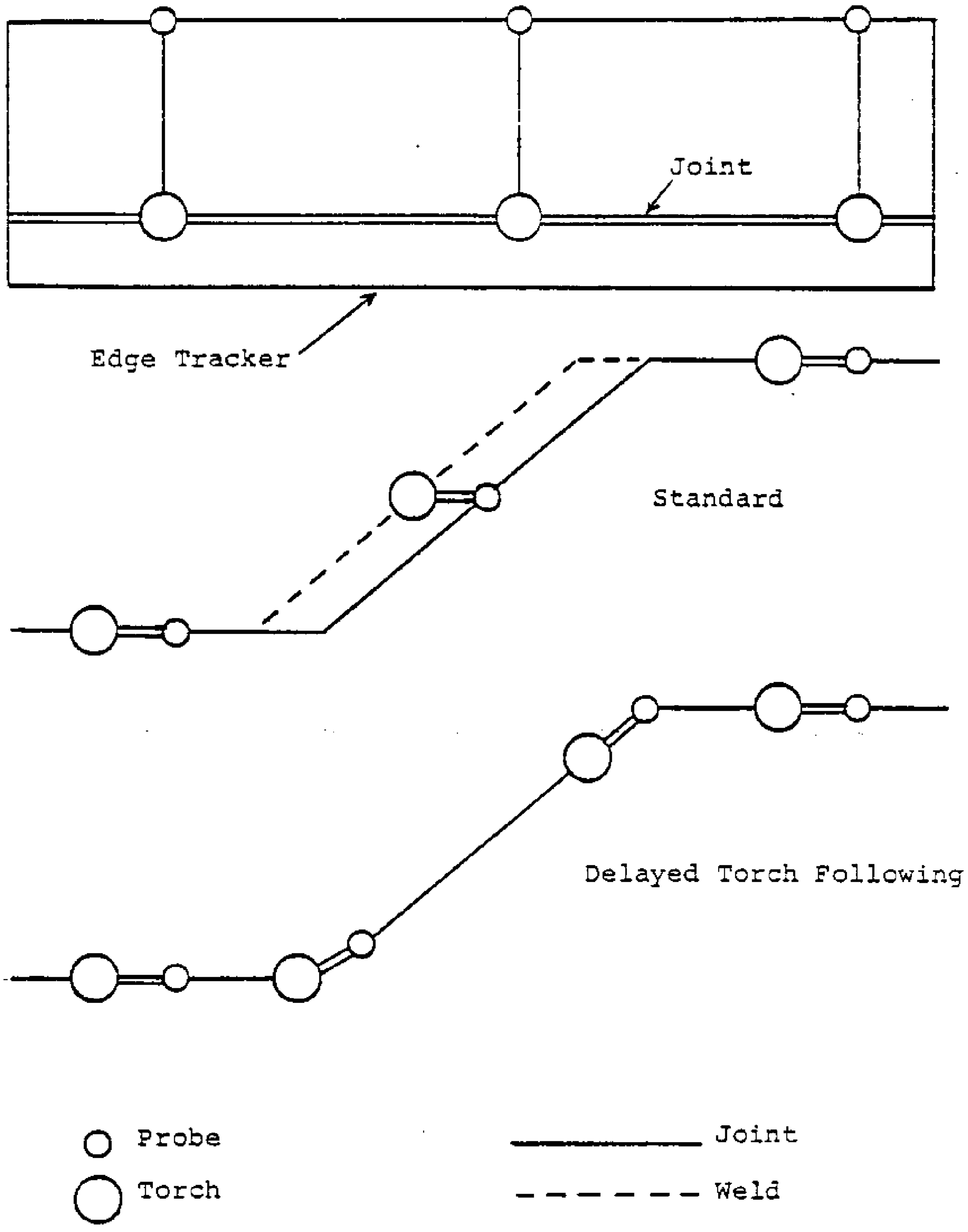


FIGURE 4.12: Seam Tracking Sensors[29]

Several different types of transducers can be used, including the following:

- Potentiometer
- Linear variable differential transformer (LVDT)
- Strain gauge
- Optical sensors

Of these types, the optical sensors are most suitable in the electro-magnetic field environment present around the welding operation. They also offer the advantages of a very fast response time, long life, and accuracy.(43)

As the needle moves along the prescribed track, the data is kept in memory and these points are recalled during the welding operation. The programming method does have some drawbacks in that considerable time is required to conduct a survey of each part, which dramatically reduces productivity. Another shortcoming arises in the fact that, once the process starts, no adjustments can be made for thermal distortion or part shifting during the welding operation.

Other types of tactile sensors can be used in determining the presence/absence of a part, and also in counting during a production process. More advanced tactile devices that are capable of determining surface roughness, hardness, and other material properties are being investigated. These sensors will require extensive research and development before they will materialize in a state that is adaptable to an industrial process. At present, most of these desired tasks can be determined using other techniques, which are more advanced. An example is the utilization of laser optics or profilometry to obtain surface roughness.

4.3 Conceptual designs of adaptive control systems

An automated flash-butt welded chain fabrication center is necessary if the chain reliability is to be substantially increased. With a completely automated system comes the requirements for more complex sensors, adaptive controls and decision-making capabilities. The types of sensors currently available, or under development, have been previously discussed, and all the pertinent production parameters were identified in Chapter 2. In order to develop a conceptual design of an adaptive control system for flash-butt welded anchor chain production, it is necessary to identify the following:

* Welding and fabrication parameters to be monitored
* Method to be used in monitoring the above
* When during the production cycle the monitoring should be conducted
* The means by which the individual sensors can be integrated into one large system,

capable of chain production and quality control.

Once these details have been determined, an attempt can be made at identifying some system conceptual designs which seem feasible for performing the required task. For the sake of simplifying this problem, and also reducing the number of sensors required, only those parameters that are directly associated with the production phase will be considered. It is assumed that appropriate quality controls during steel production were maintained so that the initial material properties (i.e., hardness, grain size, strength, etc.) need not be recertified during the process.

It should be noted that regardless of the finished product, whether it be forging billets, hot rolled bars, seamless pipe, cold drawn bars, slabs, or plates, in order to ensure a quality product it is necessary to maintain quality control throughout the fabrication process. Even if the design engineer selects the correct grade of steel, and the steel mill complies with the chemical make-up, there are still problems that can occur in the steel production. No two steel mills are alike, even if the two mills make the same products to the same specifications. By the same token, neither are the methods by which they achieve their desired quality level. With the exception of continuous casting, the molten steel must be poured into an ingot mold where solidification occurs. During the cooling process a shrinkage cavity forms which will cause defects in products formed from the ingot, if it is not completely removed.

In recent years, the steel industry has shown considerable interest in sensing equipment for on-line testing in their mills. The interest in this area is generated in the fact that it is much easier to examine a billet since it has considerably less surface area than the finished product. As an example, a 6"x6" billet has 228 sq. in. of surface area, but when rolled to a one-inch bar it has a surface area of about 1700 sq.in.(44) The economy is obviously in the examination of the billet. Further, if the billet is faulty it can be repaired and its value retained, whereas, the finished product might have to be scraped. Van Kirk(44) lists the following as in-line process, semi-finished steel inspection techniques currently in use in some American steel mills:

1) Fluorescent magnetic particle billet testing equipment-designed for handling a wide variety of lengths and cross sections in an in-line fashion at the rate of 45 billets/hour.

2) Fluorescent magnetic particle billet testing equipment-designed for handling limited size billets but at a high mill rate of 180 billets/hour.

3) Fully automatic electromagnetic billet testing and marking equipment - capacity of 25-40 ft./minute utilizing rotating eddy current sensors.

4) Fully automatic high speed electromagnetic billet testing and marking machine - various billet sizes and geometries with a feed rate of 60 ft./minute utilizing high speed scanning.

5) Fully automatic electromagnetic testing equipment - for detecting corner flaws in cast and rolled billets. Automatically programs multi-wheeled grinding unit to remove detected flaws.

6) Fully automatic ultrasonic testing equipment - locates internal flaws in steel billets in two planes and marks them for removal. Feed rate is approximately 100 ft./minute.

These methods have proven very successful in controlling the quality of steel delivered by the mills.

4.3.1 Monitoring of production parameters. Many of the previously identified production parameters will not have to be monitored because their quality assurance is being considered external to the system (i.e., material variables). Some parameters may have to be monitored almost continuously, while others may require only a single check. This wide list of parameters requires that; physical, thermal, electrical, electro-magnetic, acoustic, and hydraulic measurements be taken accurately and at high rates of speed. As an example of the numerous requirements, some of the actual thermal measuring requirements are listed below:

Thermal Measuring

1. Temperature of bar stock from preheat.
2. Monitor the flashing interface to observe temperature variations associated with flashing current changes.
3. Monitor welded anchor link cool down (or postheat) after flashing is complete.
4. Temperature of chain during heat treatment.

These are a few of the actual measurements required. In an effort to simplify this discussion Tables 4.1 through 4.3 were developed which encompass the summary of the system's overall requirements and tasks. They list the parameters, the types of sensors that could be used, and whether or not adaptive controls are applicable. Where available, information pertaining to when the monitoring should be performed is also provided.

From the results of these tables, it is obvious that there exists a wide range of sensors and monitors that can be applied to an automated flash-butt welding operation.

TABLE 4.1

SENSING REQUIREMENTS FOR WELDED CHAIN FABRICATION FLASHING PARAMETERS

PARAMETERS	SENSOR TYPE	TYPE CONTROL Adaptive (A) Preset (P)	MONITORING REQUIRED
BURN-OFF	Laser, Optical Electro-Mechanical	(A)	Continuous to Upset
PREHEAT	Optical Pyrometer, IR Thermocouple	(A)	Continuous
FLASHING VOLTAGE	Electronic	(A)	Continuous until Upset
FLASHING TIME	Electronic	(A)	Continuous
FLASHING RATE	Electronic	(A)	Continuous Feedback
INITIAL CLAMPING DISTANCE	Laser, Optical Electro-Mechanical	(P)	Intiial Check of Setting

TABLE 4.2

SENSING REQUIREMENTS FOR WELDED CHAIN FABRICATION UPSET PARAMETERS

PARAMETERS	SENSOR TYPE	TYPE CONTROL	MONITORING REQUIRED
		Adaptive (A) Preset (P)	
FLASHING VOLTAGE CUTOFF	Electro-Mechanical Electronic	(A)	Continuous
UPSET CURRENT	Electronic	(A)	Continuous during Upset
UPSET DISTANCE	Electro-Mechanical Laser, Optical	(A)	Continuous during Upset
UPSET FORCE	Hydraulic Electronic	(A)	Continuous
INTERFACE TEMPERATURE	Thermocouple IR Optical	(A)	Continuous Feedback to Upset Current Control and Upset Force Control

TABLE 4.3

SENSING REQUIREMENTS FOR WELDED CHAIN FABRICATION PROCESS PARAMETERS

PARAMETERS	SENSOR TYPE	TYPE OF CONTROL Adaptive (A) Preset (P) Reject/Accept (RA)	MONITORING REQUIRED
POST HEAT/ COOLING RATE	Thermocouple IR Optical	(A)/(P)	Continuous during Post Heat Warning only for Cooling Rate
HEAT TREATMENT	Thermocouple IR Optical (Photodiode)	(A)	Continuous during Treatment
BAR STOCK DIMENSIONS	Optical, Laser Electro-Mechanical	(RA)/(A)	OD and Length before and after Preheat
LINK DIMENSIONS	Optical Imaging, Masking	(A)/(P)/(RA)	Before Upset begins (A) After Welding (P) After Stripping (RA)
MISALIGNMENT OF LINK ENDS	Optical, Laser	(A)	Clamping grip asjustment prior to Upset
STUD LENGTH	Optical Electro-Mechanical	(P)/(RA)	Before insertion in welded link

TABLE 4.3 (cont'd)

SENSING REQUIREMENTS FOR WELDED CHAIN FABRICATION PROCESS PARAMETERS

PARAMETERS	SENSOR TYPE	TYPE OF CONTROL Adaptive (A) Preset (P) Reject/Accept (RA)	MONITORING REQUIRED
NDT WELD	Ultrasonic, Magnetic Particle, Fluorescent Particle, and Acoustic Imaging	(P)/(RA)	Monitor after NDT conducted Reject on basis of comparative imaging
CHAIN LENGTH	Laser, Optics	(P)/(RA)	Continuous measurement of five consecutive lengths. Measurement of overall shot length.

The more of these adaptive controls that are used, the higher the capital investment in the system. With the increased number of controls and sensors comes the added complexities of programming and system integration. Not all these controls are probably essential, and what each individual one contributes to the overall improved reliability may be very small. Once a certain number of these have been installed, further capital and technical investment may not be warranted. The degree to which an operation is automated should reflect its ability to achieve the desired reliability in its output product. For the case of flash-butt welded anchor chain, further studies need to be conducted to determine which controls and sensors are essential and would provide the most benefit for the system.

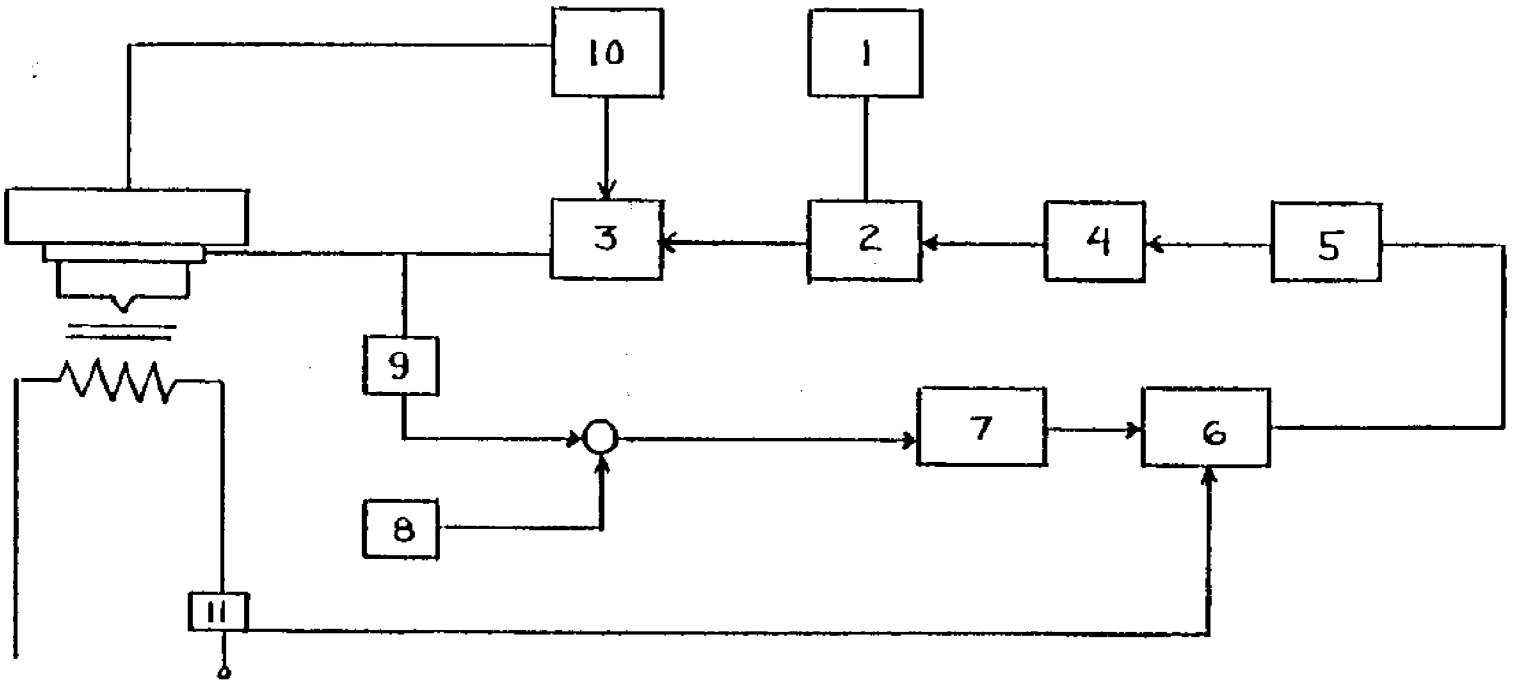
4.3.2 Platen movement control. A study of all the process variables reveals that none of the parameters are really independent variables. As each one changes, the overall process is affected in some complex manner. This interdependence is especially noticeable in the area of the flashing parameters, where the current, voltage and platen movement are very closely related. (Platen movement is considred to encompass; flashing rate, flashing time and flashing voltage cutoff.) Of all the parameters that must be controlled during the flashing operation, platen movement is one of the most critical factors effecting weld quality. Present day controls for the platen motion are based on predetermined rates of platen advance, such as linear and parabolic patterns. Because of their lack of ability to adjust to changing conditions, these controls experience difficulty in trying to achieve high stability flashing. The major heating effect of the flashing operation comes from the resistance heating of the contact bridges between the abutting surfaces. As burn-off occurs, the size and number of these contacts is constantly changing. The contacts are heated by the current passing through them, but at the same time the platen motion is compressing them and hence lowering their electrical resistance (decreasing the heating rate). From this it can be seen that stable flashing is difficult to control, and that platen motion must be kept compatible to actual burn-off rate to ensure that flashing can continue. If the burn-off rate exceeds the platen motion, flashing will eventually cease when the gap becomes too large. The other extreme results in a short circuit when the platen motion exceeds the burn-off. In order to avoid the short circuit condition many welding machines are designed with excessive power availability and higher open circuit voltage than is theoretically necessary.(45) This provides the machine with sufficient power to expel the contacts at the expense of a lower machine efficiency. Another disadvantage of this approach is that the resultant current pulse required to eliminate the large contact bridge can cause weld defects and deep craters.

According to Ji-Long,(45) the motion of the platen can be controlled such that a limitation can be placed on the size of the largest contact bridges as they form. By limiting the size of the contacts, the flashing voltage can be reduced. Platen direction and velocity are regulated by the use of the current density of the contact bridges as the controlling signal. These densities are compared to the reference value and then the speed/direction is corrected to maintain stable flashing, and to limit the power requirement for burn-off. The instantaneous control system is an electro-hydraulic servo mechanism which maintains a high precision control on platen position and velocity. This control system also has adequate frequency response to react to the rapidly changing flashing process (see Figure 4.13).

A summary of the results obtained by Ji-Long pertaining to an instantaneous platen control system follows:

1) The power required to initiate and maintain flashing is considerably reduced.

2) During the mid-stage flashing phase (heating), the average flashing current is higher than in preset platen motion equipment, even though the open circuit voltage has been reduced. This increase in current is due to the longer



1. Oil supply
2. Electro-hydraulic servo mechanism
3. Operation cylinder
4. Power amplifier
5. Preamplifier
6. Proportional amplification and correction circuit
7. Sequence control
8. Standard voltage
9. Velocity transducer
10. Position transducer
11. Current transformer

FIGURE 4.13: Instantaneous Control System(45)

bridge contact time and, hence, the overall heating efficiency of the flash welding operation is increased.

3) Increased workpiece temperatures can be obtained (see Figure 4.14) and also the resultant temperature gradient is steeper. These factors allow for the formation of a smaller HAZ during the actual welding operation, which reduces the danger of porosities. A side benefit of the steep thermal gradient is the greatly reduced amount of metal burn-off.

4) In final stage, flashing is stable and free of intermittent open circuits and shorts. This stability just prior to the upsetting action results in high quality welds with little or no contamination.

These results are quite promising, and the advantages of this kind of platen control system are very important in developing a system capable of producing high quality welds.

4.3.3 Conceptual model. In an attempt to consolidate the sensor requirements and the associated production requirements into an integrated system, a conceptual model was developed. The model, which appears in this section,

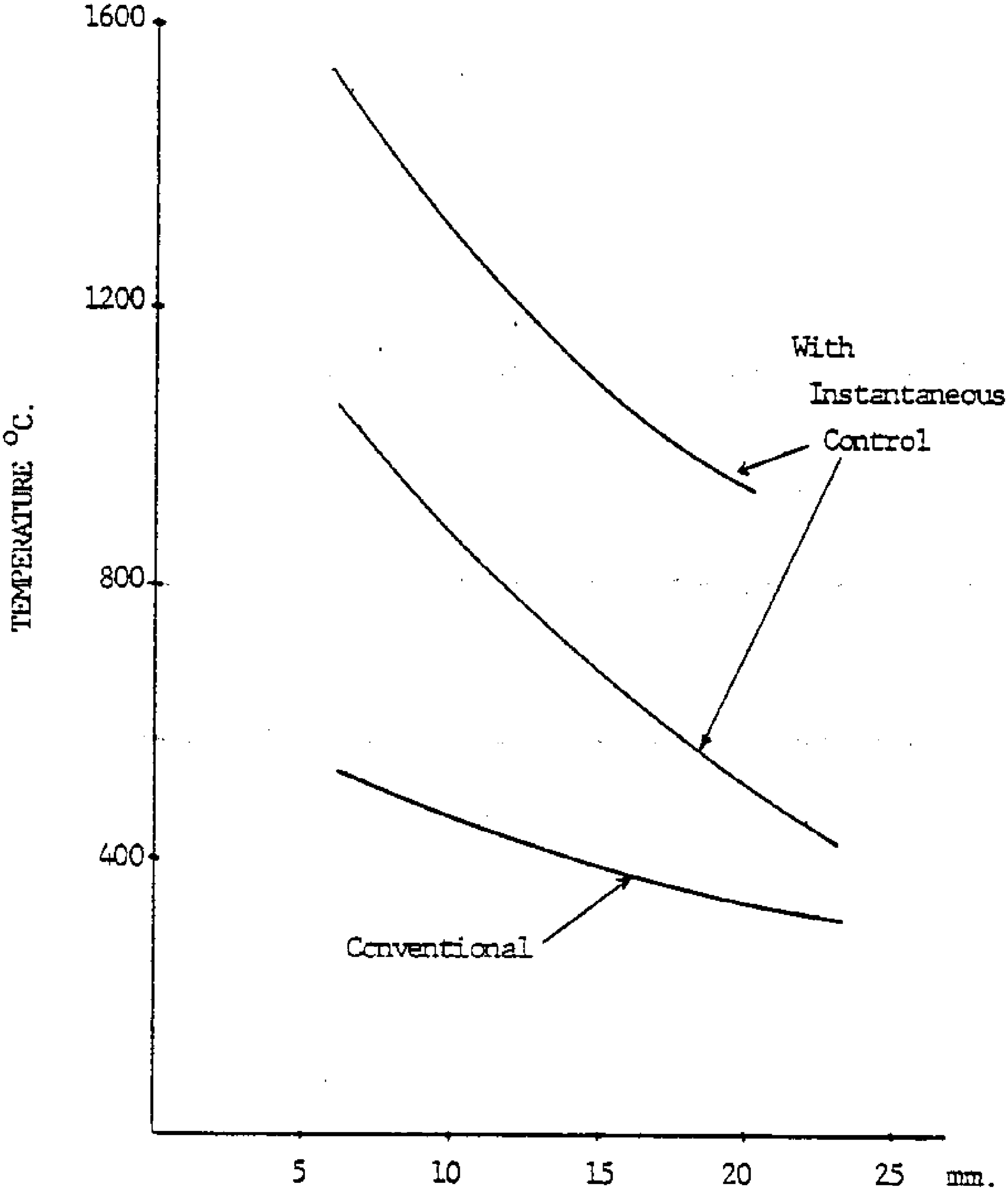


FIGURE 4.14: Temperature Distribution at Workpiece Ends(45)

is the result of combining the anchor chain production parameters, sensors, data collection, and decision making requirements into a system that could be applied to automated chain production. This model is not detailed, but is does give an indication of the large amount of information that must be processed and disseminated. Many of the sensors used may not yet be fully developed, but it is anticipated that progress will be made in these areas in the near future. Other variations of this model are possible, and it is the author's intent to present, in a graphical manner, only one possible means of achieving increased chain reliability through application of adaptive controls to an automated process.

Some areas of this automated chain fabrication process will not be easily achieved. This applies especially to the requirements for the sensor systems, the kinematics of the manipulation system, and also the image sensing and processing. Multi-sensor controlled assembly systems are feasible, but presently they take much of the technology to its present day limits. Intelligent measuring systems will find increasing application in the automation of industrial processes, such as chain fabrication, but the ease with which this will occur cannot be predicted. Estimates as to what new sensor capabilities may be developed in the near future vary considerably, and delays in implementation cannot be forseen.

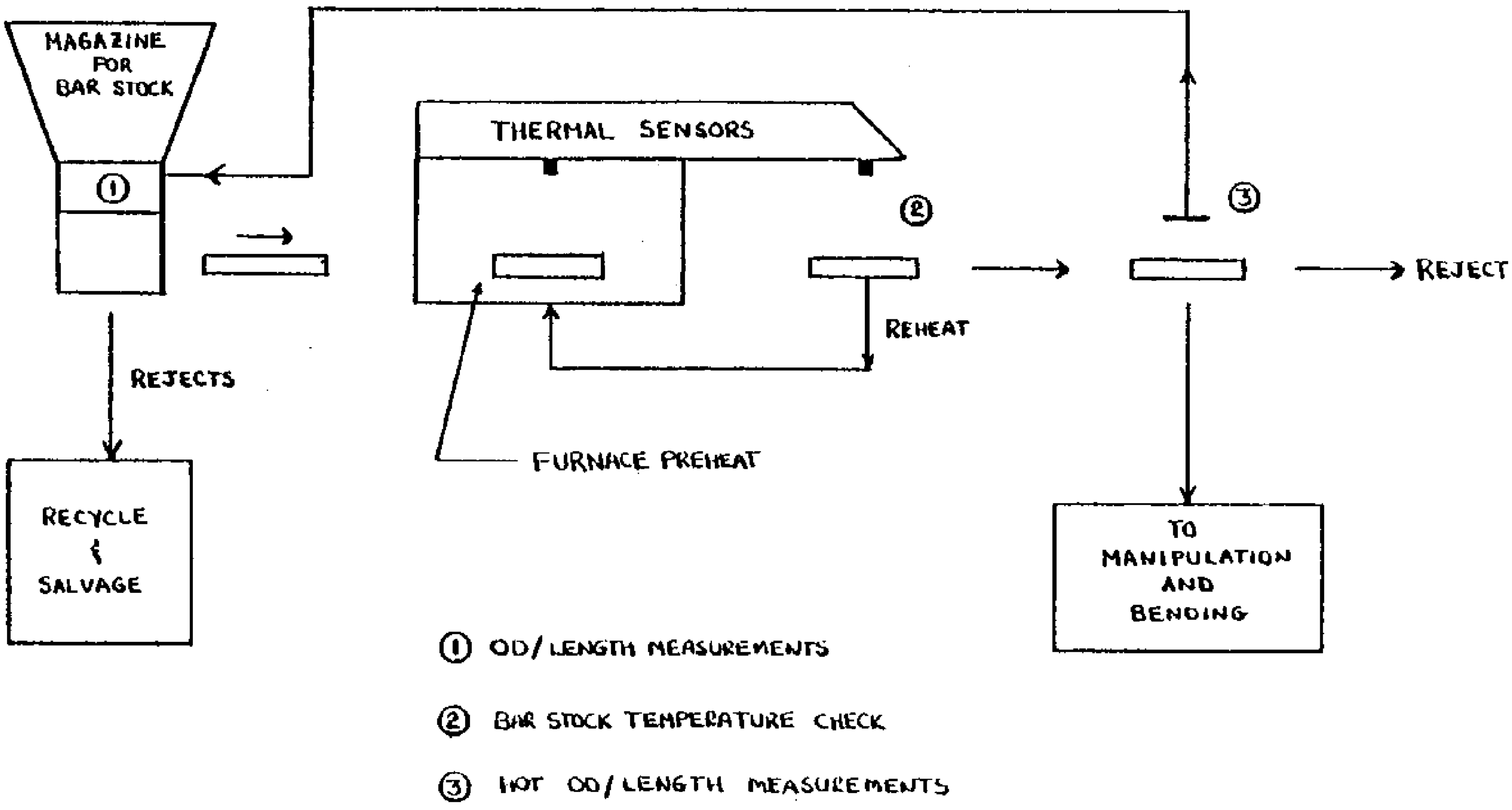


FIGURE 4.15: Automated Chain Fabrication and Monitoring System

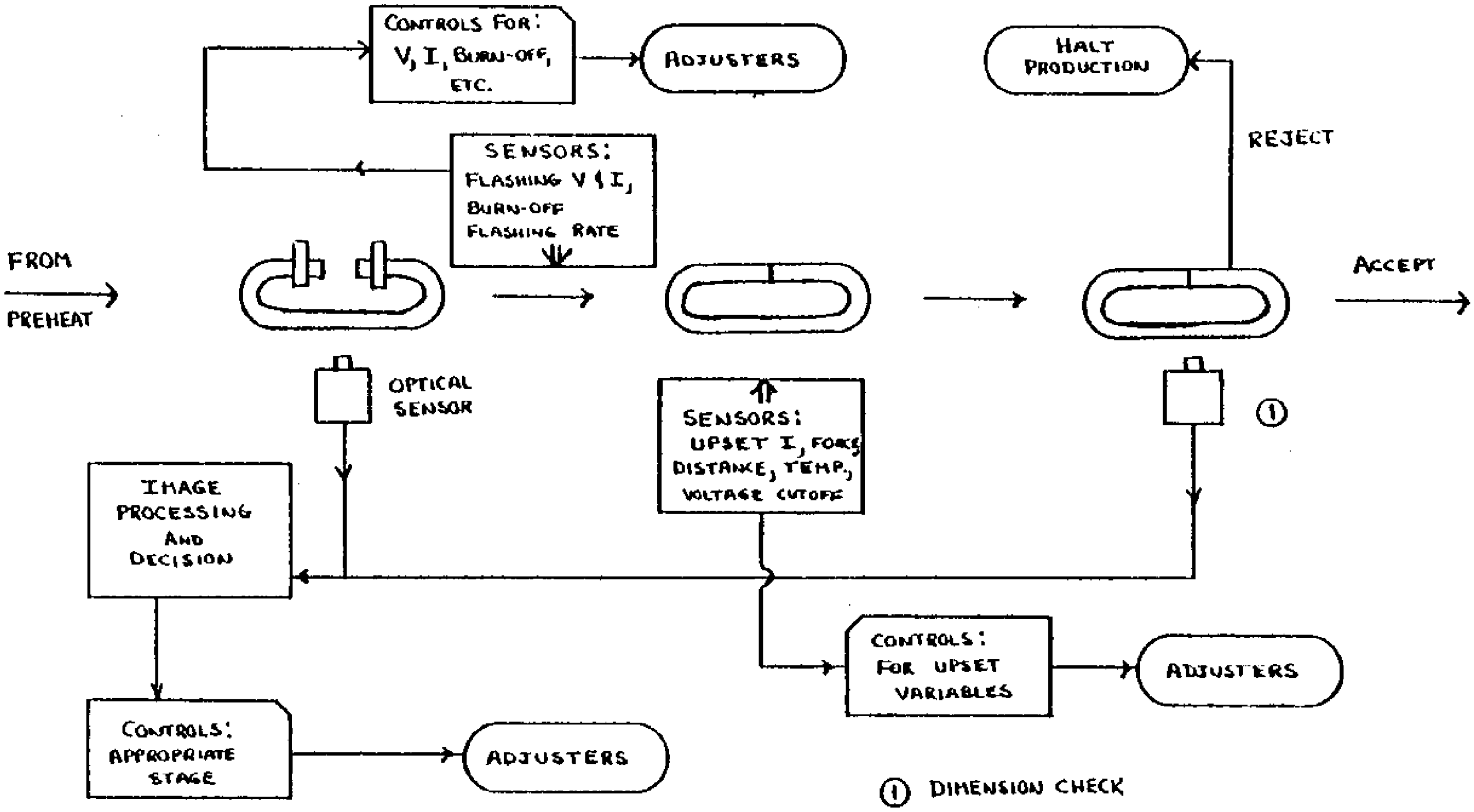


FIGURE 4.15 (continued)

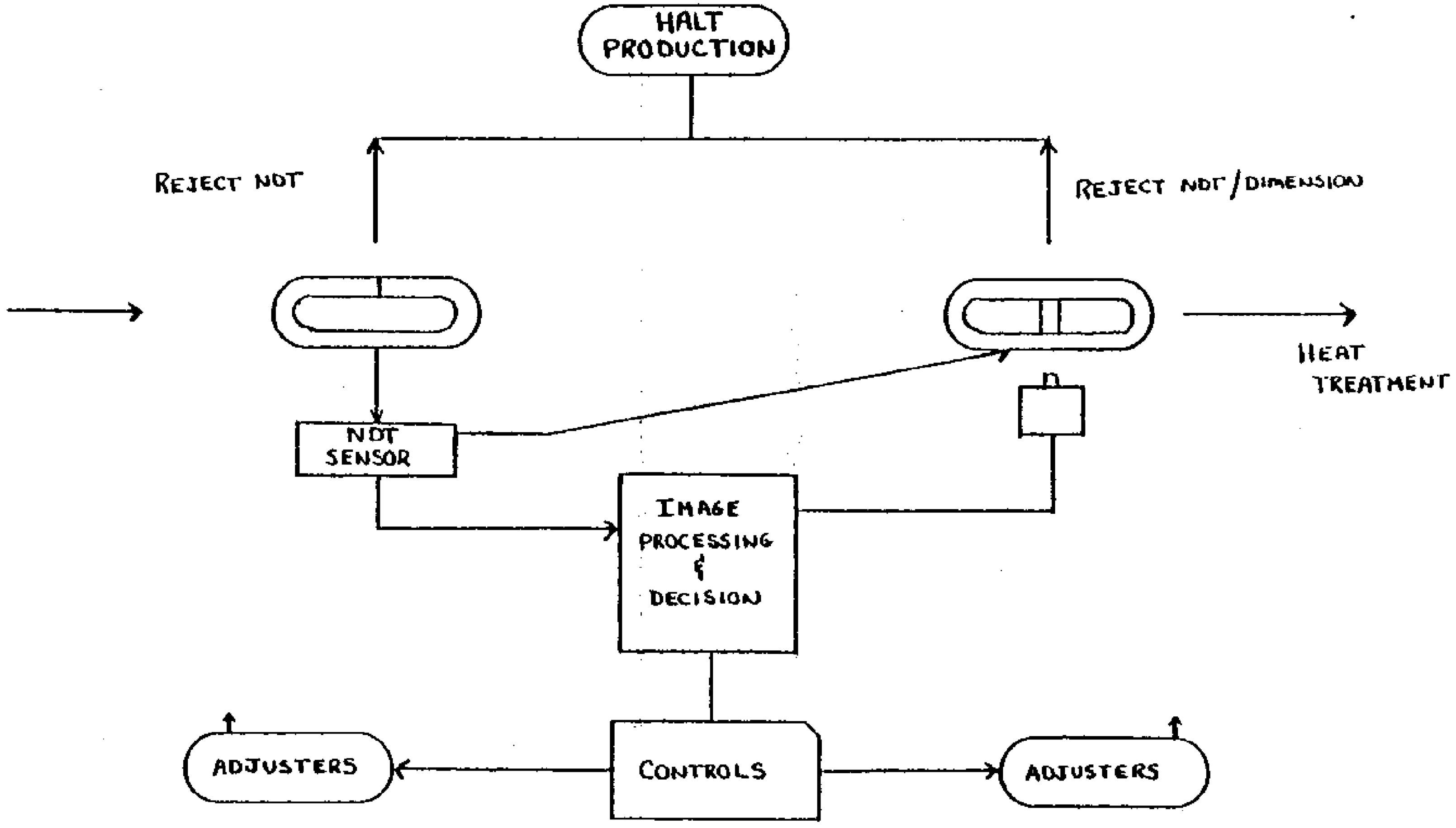


FIGURE 4.15 (continued)

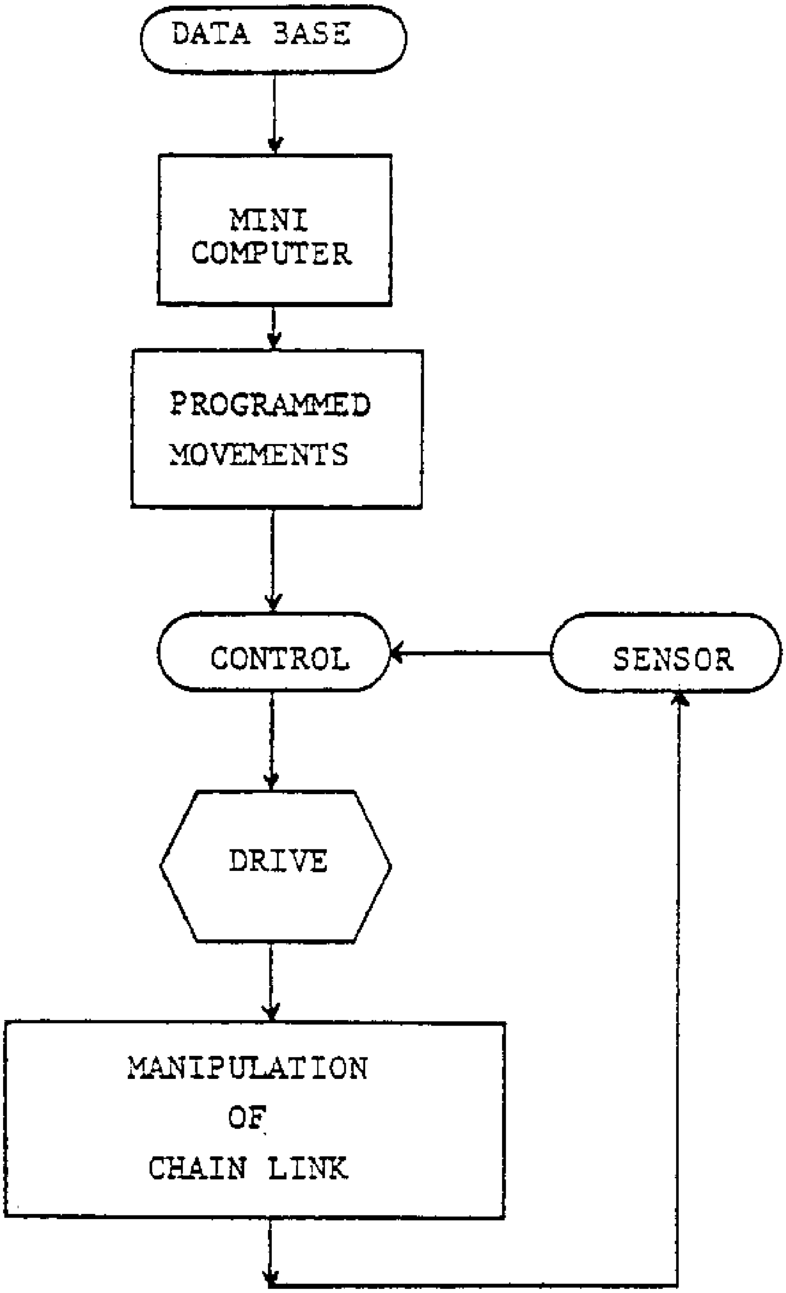


FIGURE 4.16: Coupling of Sensor to Control System for Manipulation

In arriving at this model, as shown in the preceding Figures, many sources were drawn upon to determine which type of sensors and controls would provide the best performance. The actual measurements and controls are quite complex and further research and development are still required. Some areas, such as platen motion control, show great promise in achieving higher quality welds through high precision controls. Other areas, such as NDT, still need to be improved to enable them to be accomplished at a faster rate but with increased accuracy. These developments in control equipment and monitoring devices are giving users an assurance that cannot be gained through NDT methods. Even though these devices are very useful, they should not be relied upon wholly, since to get consistently good results, quality control standards must be high.(46)

5. Methods to Reduce the Possibilities of Premature Failure of Welded Anchor Chain

In order to be able to produce a higher quality anchor chain, it is essential that the types of premature failure that can occur be identified. (Chain failure case studies are included in Appendix B.) Once these modes of failure, and their frequency of occurence are known, steps can be taken to try to improve the fabrication process by varying the appropriate parameters. Sometimes the parameter that must be changed may adversely affect other aspects of the chain quality by causing a different type of defect. In these cases, a decision must be made as to which defect is least desirable, and the parameters should be adjusted to reduce the probability of its occurence. Identification of the types of failures that occur also allows the manufacturer to adjust his quality control procedures (i.e., NDT) to ensure that the proper techniques are used to detect these anticipated flaws.

All welded chain failures are not the result of shortcomings in the chain manufacturing process. Some failures can be traced to the bar stock, which many are caused by damage inflicted during in-service use. For this reason, it is essential that the chain be inspected periodically to ensure that no conditions exist that would cause premature catastrophic failure. The inspection and testing must be continued throughout the chain's life to determine that it meets minimum standards established for its use. The following sections will investigate the causes of chain failure and attempt to establish guidance for procedures which should reduce the possibilities of premature failure of flash-butt welded chain.

5.1 Identification of problem areas of chain failure

Over the years, merchant ships have had good service performance from welded anchor chain. The British Navy has also found welded chain to perform satisfactorily under its operational requirements. Failures in chain could be caused by fatigue, wear, brittle fracture, corrosion, ductile fracture or stretching under high load conditions (see Appendix B). Sometimes these different mechanisms work together to expedite the failure of a part, such as with a combination of corrosion and wear. Many times the failure is not associated with the common link, but rather with the connecting links. As stated in the National Materials Advisory Board Report (NMAB-371)(7), when the relative number of connecting links and common links in a chain are considered, the failure frequency of the joining components is around fifty times that of the common link. This dramatically higher failure rate is attributed to the more complex design of the connecting link as well as to its inherent stress concentrations. Chain failure research conducted by Stern and Wheatcroft(46) showed that a cost-effective approach to increasing overall chain reliability would be to improve the connecting links, or to reduce the number of connectors in the chain. Some welded chain applications could be modified to use longer lengths of chain, but certain shipping operations would encounter difficulty in chain handling and stowage of long sections.

Failure in common links account for about 17% of all ship mooring system casualties.(7) Even though this represents only a small percentage of the total failures, it is important to try to eliminate potential problems wherever possible. The data from the reports already cited, as well as from other sources, was studied and some of the common causes for chain failure have been found to be the following:

1) Brittle failure
2) Lack of fusion in the weld zone.
3) Heat Affected Zone (HAZ) microcracking
4) Fatigue
5) Defects caused by the gripping electrodes during welding
6) Lack of maintenance, wear and abuse
7) Corrosion around the end of the inserted stud, resulting in the loss of the stud
8) Fracture initiated from notches created during arc welding of the stud into the link.

As can be seen, many of these causes of failure could be eliminated, or at least reduced, by adherence to rigid quality assurance procedures throughout the flash-butt welding process. It should also be noted that the corrosion problem at the stud end, and the fracture initiated from notches caused by arc welding are not failures associated with the flash welded joint. Failures have also been reported in the bar stock material itself due to internal inclusions, defects, or pipes.

A. Brittle fracture

Brittle failure of anchor chain can be readily avoided if the proper heat treatment is utilized after the chain is manufactured so that adequate toughness is achieved. In the case of flash welded chain, the chain must be properly normalized to achieve the desired qualities. By studying the normalizing parameters, the proper combination can be found for the specific chain link material. (Baldt, Inc. has successfully done this for their production line chain based on studies conducted by Battelle Columbus Laboratories.)(47)

B. Stud induced failures

The next type of defects to be considered are those associated with the stud insertion. Not all welded chain is manufactured in the same manner, and the chain design varies between manufacturers. Of the most common types in service, the following are the most prevalent:

1) Welded stud
2) Integral stud

Also found are press fit studs, but their use is being curtailed due to a record of high stud loss rates. Once the stud is lost, the chain link becomes very susceptible to twisting and deformation. This deformation can lead to failure, or at least cause malfunctioning at the anchor windlass due to the incompatibility of the elongated links and the windlass surface. For this reason it is important to maintain the link's shape by securing the stud in place.

Welded studs can be inserted in various manners. Some manufacturers weld both ends, while others only weld one end. The degree to which these studs are welded also changes, from simple tack welds to full circumferential welds. With these choices the U.S. Navy has selected to use a circumferentially, structurally welded stud, whose weld bead is located on the opposite side of the link from the flash-butt weld joint. No specific chain failure rates are available for this type of stud connection, but results from general investigations (such as NMAB) show that there can be a corrosion problem in these small crevices. Since this is essectially a design related matter, at present the only measures available to avoid excessive corrosion losses are proper maintenance and preservation.

Failures in chain link have also been reported to have initiated in the area of the stud weld. In many chain manufacturing operations this weld is treated as a secondary weld and it does not receive the attention that the flash weld receives from the testing and inspection point of view. One of the easiest means of avoiding these type of failures is to ensure that quality assurance is maintained throughout the manufacturing process. The stud weld should be inspected (NDT) to ensure that a proper joint is formed between the stud and the link. Most of the NDT methods currently available still have their shortcomings, but any of the acceptable procedures (i.e., dye penetrant, magnetic particle, etc.) could be used as a first indication of a possible problem area. The problem here in obtaining good NDT results from the complexity of the geometry of the stud joint and anchor link. Radiography may be required to check the area of the interface between the stud and link, to ensure that the arc welding didn't cause any internal defects. It is also essential that no stress concentrations are formed during the stud welding which could cause crack initiation sites. With proper controls on the arc welding, and sufficient NDT procedures, many of these potential stud failures can be eliminated before leaving the plant. Periodic inspections during in-service life could detect potential problem areas early and allow for corrective action to be taken.

The integral stud link, such as used in the chains developed by Griffin-Woodhouse Ltd, is very similar in design to the one that is produced in Die-Lock chain. By its design, it affords the support required to keep the link from kinking, while it better avoids corrosion problems because of its single unit construction. Again, no specific failure data is available for this type of stud link, so no definite conclusions can be drawn. If this chain performs like its Die-Lock counterpart, with respect to corrosion resistance, it will be easier to maintain than the welded inserted stud chain.

C. Gripping electrode defects

Some failures have been attributed to defects caused by the gripping electrodes during the flash welding phase. In these cases, several different conditions can exist which could result in a defective link:

1) Unbalanced gripping power could result in non-uniform upsetting of the link, thereby causing residual stress concentrations in the strained geometry. This could be caused by excessive wear on one dye.

2) Burn areas could develop if electrode contact area is too small for the amount of current being passed. By design, the contact areas are sufficiently large, but

> flash welding dies tend to wear causing the contact area to decrease. These reduced areas, in combination with dirt and flash that become embedded in the dies, tend to cause local hot spots and die burns.(11) These burn areas will be very susceptible to future cracking.

Both of these production process-induced defects could be avoided if an established equipment maintenance and inspection procedure is followed. Dyes should be inspected before the start of a production run and then periodically throughout the process. The frequency of inspection would vary for different chain sizes and materials, but it should be selected so as to ensure that the proper pressure and contact are present on the dyes. This requirement might cut into production time, but the benefits that are gained in chain quality will far outweigh production losses. Even with the dye inspection, the link surface areas that are gripped by the dyes should also be inspected for burn marks and indication of dye slippage (i.e., grooves, scratches). If burn marks continue after the above procedures are followed, the possibility of inadequate dye design should be investigated.

D. Lack of fusion in the weld zone

Incomplete fusion can be caused by insufficient upsetting force or distance, and also by unfavorable temperature distribution at the weld interface. These problems have resulted in some flash-welded anchor chain failures. Similar problems were encountered in the railway industry during the production of their continuous welded rail (CWR). Even though the failure rate for flash-butt welded CWR was considerably lower than any other method, (0.0043 failures per 100 weld years), many of the failures that occurred were linked to incomplete fusion.(48) As discussed in Chapter 4, there are ways of avoiding this lack of fusion through monitoring and sensing devices. Additionally the suggestion of an instantaneously controlled platen motion could feasibly eliminate the unfavorable temperature distribution and upset distance.

Another method that has been successfully implemented by the rail industry was a modification of the flash welding equipment to ensure adequate upsetting force was available when needed. During the production of CWR for a South African railway, it was discovered that incomplete fusion was occuring at the flashing surfaces.(49) Further investigation revealed that the welding machine did not have a smooth enough transition between flashing and upsetting. Since the main upsetting actuator operated by means of an air-hydraulic intensifier unit, it was found that there was insufficient air in the piping system to act on the intensifier. This caused a slight hesitation in the application of the upsetting force, resulting in defect formation. The problem was alleviated by the installation of an air flask which was capable of supplying the instantaneous volume of air required. Various welding machines control the upsetting operation by different means, but this particular solution shows the importance of the smooth transition required between the various stages of the overall process.

The Soviet pipe manufacturing industry has also developed an approach to reduce the amount of incomplete fusion found in flash-butt welded specimens. Researchers at Paton Welding Institute developed a method of vibrating the workpiece to help the fusion of the interface.(50) Since the heat for flash welding comes from the impulse flashing of the work pieces as they approach each other, the researchers found they could achieve optimum electrical resistance by vibrating the workpieces (see Figure 5.1). A servo-control system automatically regulates the mechanical vibration at a frequency and amplitude that produces a stable circuit impedance. These controls therefore produce a uniform heating of the workpiece surfaces. Using this method, incomplete fusion can be greatly reduced, if not eliminated completely.

E. HAZ Microcracking defects

Overheating during flash-welding can cause problems in the HAZ, such as fissuring at the grain boundaries. These defects are associated with uneven temperature distri-

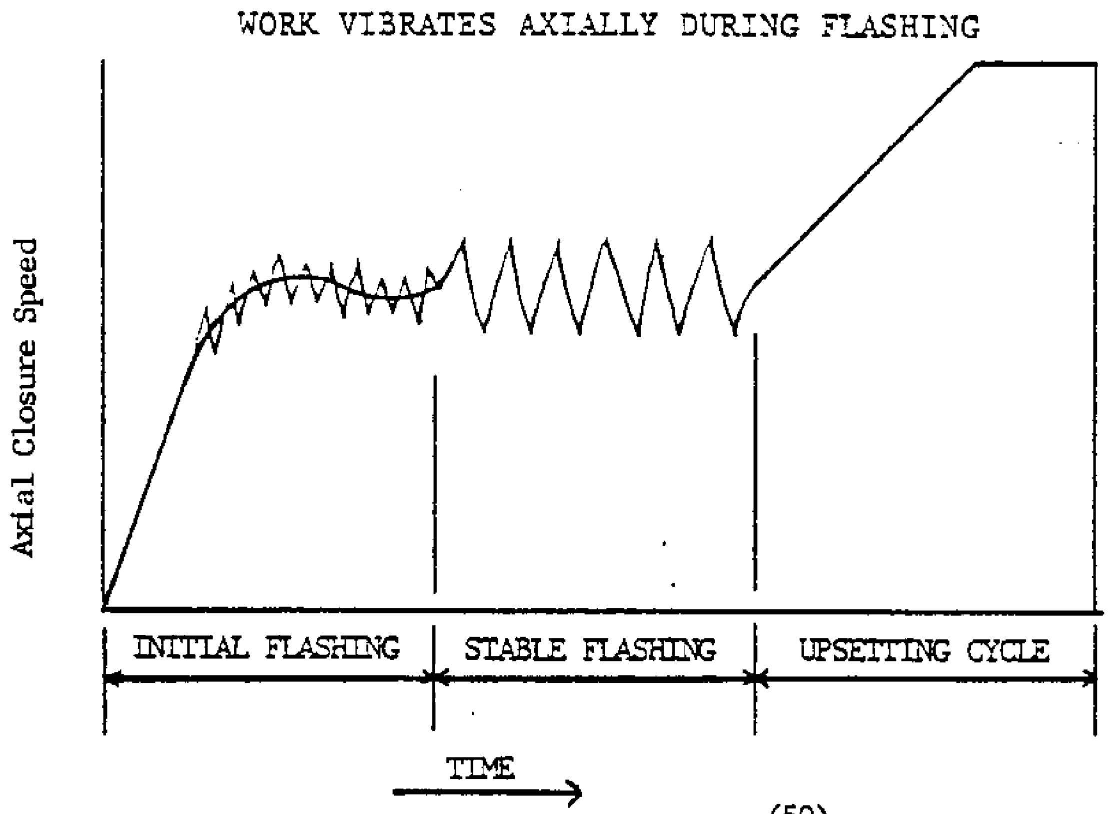


FIGURE 5.1: Vibrating Platen Motion(50)

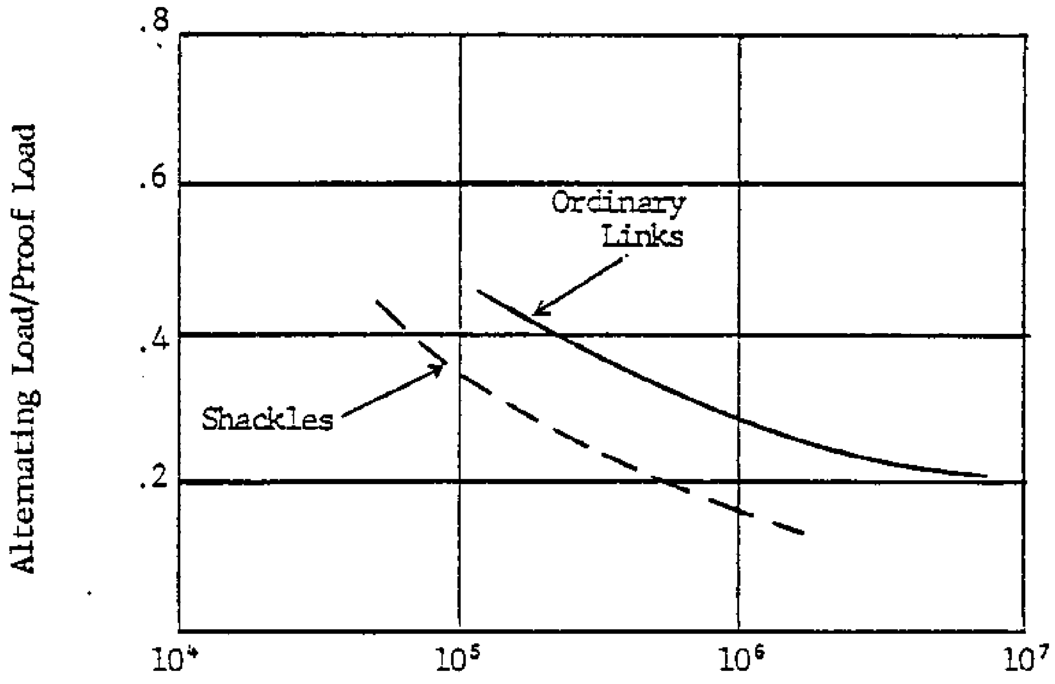


FIGURE 5.2: Number of Cycles to Failure(51)

bution resulting in high temperature regions which are susceptible to microcracking. Proper controls and quality assurance can eliminate most of these defects, and combined with adequate NDT those that do occur should be detected before the chain is placed in use. New improved control methods, such as the instantaneous platen motion control, result in the formation of a more uniform temperature distribution and also a smaller HAZ. This will result in the reduction of occurence of overheating conditions and, therefore, reduce microcracking. A similar result would be achieved by use of the Soviet welding method discussed in the previous section.

F. Fatigue failure

Whether or not fatigue poses a problem in U.S.Navy applications is a question that has not been completely resolved. There is general agreement that high cycle fatigue cannot be a problem with naval ships, but it may pose a substantial problem for offshore oil rigs.(47) Possibility exists for low-cycle,high stress fatigue cracking to develop under the proper conditions. Provided that the chain is periodically inspected, these fatigue cracks should be readily detectable. Considering that crack initiation occurs at a fraction of the time required for fatigue fracture, sufficient time should be available to take corrective action to avoid catostrophic failure.

At present, relatively little data is available pertaining to fatigue strength of high grade anchor chain, especially for dimensions greater than 2½-in. diameter. Figure 5.2 gives a normalized S - N diagram for 2-in. oil rig quality chain.(51) This curve also depicts a predicted life for connecting links for comparison. As stated earlier, the graph implies that high-cycle fatigue could be a problem in offshore rigs but not in naval surface ships.

The fatigue life of a welded chain can be influenced by several factors. A study conducted by Ramnäs, Sweden(52) concluded that the form of the links and the surface conditions of the links can considerably reduce fatigue strength as compared to the fatigue strength obtained through conventional fatigue testing methods. Van Helvoirt (53) suggests that the preheating before bending the chain link should be controlled to avoid the formation of "ripples" at the inside of the link bends which can act as fatigue-crack initiation sites. By avoidance of these flaws, and other factors, the fatigue life of the welded chain can be improved.

G. Failures due to wear and abuse

Due to the lack of documentation associated with mooring failures, little information is available as to the impact of wear and abuse on actual chain failure rate. The U.S. Navy and the regulatory societies have established wear criteria which dictates when the chain must be replaced.

Guidance is based on overall link diameter changes and does not always consider other parameters. The degree to which chain abuse during handling and stowage influences the chain failure rate is even more vague. Buchanan(54) reports that the high number of breaks that occur in the first and second lengths of chain may be the result of careless handling of the chain when the anchor is being housed in the hawsepipe. Buckle(55) considers operational requirements and gross overloading of the chain the determining factors in the frequency of chain failure and not the individual link defects.

Many merchant ships utilize their anchors for maneuvering and even stopping. Under these abusive conditions extremely large strains can be produced in the chain links. The original design did not anticipate these requirements and it is unreasonable to expect the chain to perform satisfactorily when treated in such a manner. Many of these commercial failures could be avoided if the operating personnel were made better aware of the chain strength limitations and also if they were better indoctrinated in proper ship handling procedures. When several ships can report the failure and loss of three and four anchors in a period of a few years,(55) it becomes apparent to the author that some additional ship handling training is required. This high rate of chain failure appears to reflect more upon the ship operations than on the quality of the moorings.

Chain wear is not always addressed in discussing the failure of ship moorings. Many consider chain wear as more of an indicator than an actual potential chain fault. Common practice is to use wear readings solely for decisions on whether a length of chain needs to be replaced. By the time the chain is replaced, based on minimum remaining diameter readings, considerable changes may have already occured in the chain's overall strength and quality. Most chains that are removed from service are taken out because of excessive wear. These wear limits were established to avoid the increasing risk of fracture or excessive dynamic loads due to the reduced diameter. It should be noted that the macroscopic crack growth rate in most metals is driven by the fourth power of the stress in the member,(56) and hence, a relatively small decrease in the links section modulus can impose very large crack growth rates. The ability of the chain steel to resist both fracture and wear is a function of its mechanical properties, and in many cases, these two demands are in direct conflict with each other.

Various types of wear can take place during a chain's in-service life ranging from adhesive wear caused by the mutual rubbing of the links together, to the ploughing and gouging caused by the chain link coming in contact with a hardened rough surface. If sufficiently deep scratches are worn into areas of the link that are normally under high stress, greater stress concentrations could be formed which could lead to crack initiation and eventual failure. Under normal loading conditions, when the ship is at anchor, the chain aligns itself such that the heaviest wear occurs at the link to link interface known as the grip. Within this area, the ship's motion in response to the induced wave action causes the links to slide across each other under considerably high load. Considering that these contact areas are lubricated at best by seawater, and in other cases unlubricated, the wear coefficients can be relatively high. The sliding distance may not be large, but over a period of time a considerable amount of material can be removed from the grip areas. Combining this wear with the corrosion effect of the chain's saltwater environment can result in substantial strength and material losses.

Another area of chain wear is along the chain link edges as it passes over the ship's fairlead or as it encounters the anchor windlass mating surface. Here we are sometimes faced with a difference in material properties of the two surfaces (i.e., hardness) and different wear rates can occur. In these cases, the major damage sustained by the chain is caused by improper mating at the windlass surface and also by a snapping/impacting action at the fairlead. This particular action at the fairlead has been attributed to many link failures within the first outboard shot of chain. As the wear progresses, improper fit-up can occur at the windlass and this in turn can cause uneven loading and bending of the links. This combination of effects must be avoided in order to maintain chain integrity and usefulness. Periodic inspections can eliminate most of these problems when combined with proper handling and stowage techniques.

5.2 Procedures to reduce in-service premature chain failures

The previous section dealt with identifying various types of defects that have been known to cause chain failure. Methods of how to modify the fabrication process to avoid these defects were discussed, and some conclusions were drawn. Even with the implementation of better manufacturing procedures, and more extensive quality assurance, some chain will be placed in service that may be marginally acceptable. This chain, or even the best chain, can develop faults and defects from its shipboard environment (i.e., wear, corrosion, etc.). In order to maintain chain quality, an on-going maintenance and inspection procedure must be followed throughout the chain's life. Three areas will be discussed as possible means of achieving the goal of reliable chain. These areas are: in-service inspection, maintenance, and modification of materials and machinery used in mooring systems.

A. Maintenance

The area of chain maintenance is in direct opposition to the abuses in handling and stowage discussed earlier. In order to prevent a premature chain failure, it is imperative that a good shipboard maintenance program is established. Within this general maintenance classification there are many types of maintenance that can be applicable to any system:(57)

1. Recurring maintenance - a work requirement that is performed on a scheduled basis to ensure continuous reliability of the equipment.
2. Preventive maintenance - shipboard servicing of equipment using prescribed procedures and accomplished at specific time intervals. The objective of the maintenance is to detect and correct any conditions which reduce the system's efficiency.
3. Restorative maintenance - this is a refurbishment evolution performed by the ship's crew or other maintenance activity in accordance with established guidelines and specifications.
4. Corrective maintenance - is classified as maintenance that is required to restore the

> equipment to operating order. These are unscheduled repairs, but are still performed using published technical guidance.

All of these types of maintenance play an important role in ensuring that the proper working conditions for the system are being maintained. No longer can corrective maintenance be accepted as the only necessary phase. Most potential problems can be detected and corrected early, and for this reason all of these areas should be included in the shipboard mooring system maintenance program.

Of all the maintenance areas, possibly the most important one is that of preventive maintenance. The U.S. Navy has been very successful in reducing equipment failure and "down-time" by implementing a rigorous preventive maintenance system (PMS). Over the years, this system has shown its benefits by drastically reducing common failures in different equipment through the requirements of regular periodic maintenance. These maintenance requirements may entail test operation of the equipment, tolerance readings, lubrication, painting or simply a visual inspection. A similar system should be implemented throughout the shipping industry, to ensure that the system quality can be maintained. One of the most important outputs from a system of this type is the feedback information that is generated from system failures. From the documentation of these failures, trends can be established and possible solutions to these problems may be developed. With accumulation of sufficient data, predicted failure rates could be determined or possible design changes could be accomplished.

For the particular case of anchor chain maintenance, a regular schedule should be followed. The following are suggested areas of possible maintenance action that could be accomplished during in-service operation. They are arranged in chronological order, starting with the installation of the chain aboard ship:

1) Chain locker - the chain locker should be properly cleaned and preserved (painted) prior to chain installation. Any accumulated water, or potential water sources should be eliminated.

2) Chain installation - ensure that chain is properly preserved and cured prior to stowage. Make sure chain is handled and stowed properly, avoiding undue twisting and abuse.

3) Operational - check fit-up of chain and windlass, stoppers, pelican hooks, etc. to ensure that the chain is not being subjected to excessive bending loads. This should be checked every time the anchor chain is used in a mooring evolution.

4) Cleaning/Painting - whenever feasible the anchor

chain's rust and scale should be removed and a preservative coat applied. This is sometimes difficult to accomplish depending upon the ship's operating schedule, but during inport periods some maintenance can be accomplished. In this same area it might be possible to have a thin layer of lubricant applied as the chain is brought in for stowage, to lessen the chain wear and also corrosion.

5) <u>Overhaul</u> - during periods when the ship is in for extended repairs, the anchor chain could be scheduled to be removed for cleaning and preservation. During this period the chain locker should be preserved. At the time of re-installation, the ends of the chain should be reversed so as to develop a more even wear on the outboard shots of chain. Records should be maintained of these reversals, and over a period of time various sections of chain could be exchanged at the connecting links to further reduce wear. This is a time consuming evolution, but when accomplished in conjunction with other ship repairs, the monetary cost is not that great and no operational time is lost.

Again it should be emphasized that documentation and record keeping of all preventive maintenance will benefit all concerned. Equipment histories will be easy to reconstruct and predictions of anticipated failures can avoid catastrophic results. The more preventive maintenance that is regularly accomplished will be reflected in a large reduction in corrective maintenance required.

B. Inservice inspection

Many times it is hard to distinguish between preventive maintenance and in-service inspection. Under some scheduled PMS the requirement is to "inspect" some aspect of the component or system, and usually this is not an in-depth examination. Usually, if the visual inspection is satisfactory, the remaining steps can be ignored (i.e., "if no visual cracks are detected go to step 10"). In order to maintain a highly reliable anchor chain, regularly scheduled detailed inspections should be conducted. For these reasons we have to resort to NDT procedures designed for in-service use.

NDT has its limitations; certain flaws can be overlooked, some technicians lack experience, and the geometries of certain components present particular problems. Higher strength metals require the detection of smaller and smaller critical crack lengths, hence increasing the possibilities of missing a flaw during inspection. Another problem is the initial identification and detection of a flaw in a large area. If the general area of a possible defect can be localized, there is a good chance that it can be found by NDT. Table 5.1 shows some of the many NDT techniques and applications available for use today.

The U.S. Air Force conducted an evaluation of present-day NDT reliability and came up with the following conclusions:(58)

1) The overall NDT and inspections reliability may be less than anticipated.

2) The assumption that the more formal training received the better the inspector, does not hold true. Actual studies indicate that once formal training has progressed beyond a level of sufficiently acquainting the tester with the technique and background of the test, additional training had questionable value.

3) The number of years experience does not seem to affect the detection rate. However, poor performance can be slightly moderated by experience.

4) The number of times a technician performs NDT within a time frame does not effect his performance.

TABLE 5.1

CURRENT NDT METHODS

Method	Elements	Application
Liquid Penetrant	Materials and equipment Cleanliness of part surface Applications Emulsification Removal Development Interpretation	Surface flaws in forgings, extrusions, weldments, and some castings.
Magnetic Particle	Materials and equipment Relatively clean surface Flux lines - orientation and intensity Solution application Interpretation	Surface and near-surface flaws in ferro-magnetic materials -- forgings, weldments, extrusions
Radiography	Materials and equipment Exposure technique Film processing Interpretation	Flaws (mostly subsurface) in weldments, castings, and forgings
Eddy Current	Equipment Frequency Field configurations Display of desired parameter Interpretation	Surface flaws Conductivity
Ultrasonic	Equipment Transducer characteristics Return signal processing Interpretation	Flaws (mostly subsurface) in plate, forgings, and some castings

An area of possible partial improvement lies in the elimination of poor inspectors through recertification procedures and evaluation of past performance. The human factor plays a large role and care must be taken to ensure that the individually assigned task is small enough to accomodate the vigilance required for a high degree of flaw detection, while still proving to be economically feasible. The technicians must perform monotonous, repetitive work and they must still be alert to the smallest defect or flaw. Somehow the monotony of the work must be lessened by automated means or different testing procedures.

Even with the aforementioned shortcomings, NDT is growing and is being more widely accepted as an important tool in the overall effort to solving in-service inspection problems. Three of the main values of NDT are:

1) Higher reliability and safety of products
2) Lower inspection costs
3) Prediction of the life cycle of the system or component.

Many engineering projects utilize materials near their mechanical and thermodynamic limits which can bring about catastrophic results if the wrong conditions are met. The use of NDT in field operations to screen out flawed material before additional damage can be incurred is becoming common practice, and this becomes more important as the value of the product increases.

In order to obtain meaningful results during one anchor chain inspection, NDT needs to be expanded from simple measurements to the broader non-destructive evaluation (NDE) function. NDE also takes into consideration what the measurement means, and is prepared to make a decision based on the evaluation. A relationship must be developed between a measurable NDT material characteristic (i.e., crack length) and the actual in-service behavior. With gains in methods of NDT, mere flaw detection will not be as important as the quantitative information obtained, such as size, shape, and orientation. By applying these quantitative values to such things as fracture mechanics theory, much useful information can be obtained.

One of the major problems in the development of field NDE is how to determine the "extent of damage" to the area under investigation. The solution to this problem seems to center around the use of computers programmed to apply fracture mechanics or other scientific methods to analyze the data obtained through the various NDT. By comparing the data against known standards, they can decide if the defects are of sufficient character to warrant concern for the reliability of the product. The programming is complex, as is the theory involved, and the lack of many acceptance standards also impedes the rapid development of this field. It is important that other information is fed to the system, including projected loading conditions and environment, so it can be anticipated if the present status will deteriorate in the near future. This information is used to make an estimate of the remaining useful life of the product under the anticipated conditions.

With the objective of achieving an effective chain inspection procedure in mind, the following is suggested as a possible approach.

Visual inspection - quick identification of possible problem areas, which narrows down the test area. Since this requires little cost and manpower, it should be conducted at every opportune time.

Dye penetrant/magnetic particle - either of these methods would offer a quick check of surface indications that may have been detected during visual inspection.

Ultrasonic inspection/radiography - these tests could be used when other NDT methods have suggested that defects may exist. A regularly scheduled UT inspection could prove very beneficial to proper chain maintenance.

All of these methods could be used in their traditional manner, but several of them have potential for great improvement.

The ultrasonic and radiographic combination of tests may offer the best prospect for future in-service chain inspection procedures. With advances in ultrasonic imaging it could be possible to scan the chain as it is being hoisted aboard, to detect any flaws or defects. A portable scanning device, such as those developed to inspect railroad rails(39) could be used. This would allow a single technician to scan the chain at a relatively high rate of speed compared to other NDT methods. According to the research of Thomas and Rose,(59) who developed a UT inspection system for hull plating, the use of high speed computers and microprocessors can greatly simplify the problems in evaluating the multitude of data provided by the UT sensors. If an area of interest has first been determined, such as the weld joint, a microprocessor can be effective in conducting ultrasonic evaluation for work in the field or for shipboard use. The system can scan the chain, record pertinent data, and determine the complete picture of the extent of damage. Any questionable areas could be checked by radiography. This same equipment is capable of monitoring damage in these areas, and detecting any growth of defects during the service life of the chain. Development of this type of system to inspect chain may find difficulty in overcoming the problems posed to UT by the chain link geometry. These complex geometries cause many erroneous signals, which reduce the test methods reliability. Size and cost limitations might also restrict this type of system from being implemented aboard ship.

Another possible alternative to this type of testing would be to have an equivalent land-based system that could conduct periodic chain inspections for the ship. For use in a homeport environment, this inspection system could be based on a barge-type operation, whereby the ship being serviced could accomodate the test facility alongside. This type of arrangement would allow for the ship's anchor chain to be conveniently faked-out on the barge's deck for inspection, without actually removing it completely from the ship. The inspection time could also be used to clean and preserve the chain after the UT and radiography was complete. Facilities of this type could maintain chain data for the ship and could also become actively involved in chain maintenance. This type of operation would be comparable to an ultrasonic transit rail testing vehicle (SRS 802) which was developed by Sperry(60) to detect flaws in rails. This vehicle has had very good success at a reasonable cost, and it appears that a similar system could be applied to chain inspection.

C. Modification of materials and equipment

As discussed earlier, a large majority of the mooring system failures appear to occur in areas other than the flash weld or even the common link. A large number of connecting links, shackles, and windlasses have failed resulting in major losses. For these reasons, it appears that the possibility exists that many of the system components are not really compatible with each other. In the past, each time a failure occurred, the particular element that failed was investigated and some conclusion was drawn. Since the links, shackles, and connectors are all parts of the whole anchoring system, any failure should be analyzed as a system failure to determine what factors may have contributed to the situation. With proper documentation of these failures, it is possible to determine what parts of the system have to be modified in order to have a more reliable state.

Several articles have been written about anchoring and mooring equipment, such as by Buckle(61) and some have concentrated on the inadequacy of certain components such as anchors (Bruce).(62) Each article has addressed a particular point but they all indicate that the anchoring equipment must be treated as a system. A good number of ships in service today do not have systems that were designed for them, but have merely acquired stock items which appeared to be adequate for the ship's tonnage and gross characteristics. Many of the failures that have occured may have been avoided had this not been the case. Some designs of fairleads are inadequate and cause undue bending in the chain, while certain stopper designs put undue stress on the chain links. An effort should be made to determine these shortcomings in design, and to take corrective action to replace or upgrade equipment to the proper standards. Higher mooring system reliability can be obtained through these efforts than could be expected to be achieved through better chain manufacturing procedures. Both areas can offer some improvement, but by far the sizable gains lie with the improvement of the deck gear connecting and handling apparatus.

6. Conclusions and Recommendations

An attempt was made to review the historical developments that took place which have allowed us to reach our current state of technical knowledge in anchor chain manufacturing. Much has been learned from past experience, but many questions pertaining to the complexities of anchor chain stresses, geometry and loading conditions have yet to be answered. Many of the flash-butt welded anchor chain fabrication parameters have been identified and the relative importance of their influence on weld and chain quality has been discussed. The interactions of these variables is quite complex, and the true impact of an individual parameter change is very difficult, if not impossible to determine. Various researchers have developed equations which describe the interactions of a few parameters (i.e., flashing parameter), but currently no simple equation exists that relates all the production variables. Because of these shortcomings, each phase of the chain fabrication process is usually studied separately, thereby avoiding dealing with the uncertainty of the transition areas between phases (i.e., flashing to upsetting). In order to better control and understand these parameters, the system must be studied as a whole so that the real influence of variations of parameters can be learned. The area of platen motion needs to be investigated further, so that an optimum method can be developed for controlling this motion.

The solution to the heat flow problem in the welding of anchor chain was modelled as an instantaneously applied heat source. All surface losses (convection and radiation) were ignored in an effort to develop a simplified model. The test runs that were conducted using a linear flashing pattern showed good correlation with available experimental data, except at large distances from the weld interface. At these larger distances the computer-generated temperatures were considerably lower than the experimental values. The results from the parabolic flashing pattern showed larger temperature differentials from those obtained from laboratory data than from the linear model.

Temperature variations could be caused by over simplification of the model and by neglecting the arcing heating effect that is present at the real interface. All the curves followed the proper trends that were expected, but the thermal decay seems to be dominated by the instantaneous distance from the interface more in the model than in real life. Another very influential factor is the material's thermal diffusivity which could have considerable variation within the temperature range being studied. Also, the time interval over which the temperature is reviewed, greatly influences the outcome of the temperature profile. Any further investigations in this area should concentrate on upgrading the model to better reflect the real conditions present during flashing. The model may become quite involved, but the results would then much better approach the experimental values.

In-process sensing and control appears to be the solution to many of the shortcomings of the manufacturing process. The chain's overall quality is greatly effected by small, fast changes in certain parameters. Many recent investigations in particular have established requirements for very stringent platen motion control. The only way to effectively deal with these conditions is by integrating the system to computer control. The chain manufacturing base must be modernized by bringing in more state of the art technology. Engineers and manufacturers must be able to keep an open mind to innovation, and to follow through in implementing improvements that will ultimately integrate welding and other functions into computer based manufacturing. It must be realized that control and monitoring devices are not fail-proof, and that they cannot accomplish all tasks that are required. In the same light they cannot be relied upon to do the entire task of monitoring and control. The only way to achieve consistently good quality welded anchor chain, is to ensure that quality control standards are high and maintained throughout the manufacturing process. Monitoring and control systems should be used as a back-up system to an already well established engineering base.

Many advances have been made in recent years in the development of reliable NDE. Rapidly developing computer technology, as well as advances in fracture mechanics analysis, have brought about remarkable results in material evaluation. Some of the current existing technology has been presented to show what automated means are available to industry, and how they may be adapted to field in-service inspections. With escalating raw material costs and large capital investments into some production methods, it is essential that NDE be further developed and implemented so that these materials are not wasted. One of the major needs of NDE is the development of reliable standards which can be used for data comparison. Without good standards, the most sophisticated computer and analysis system is worthless for making predictions and evaluations of material.

Non-destructive evaluation has been successfully applied to many areas of manufacturing, such as the tire, aircraft, steel, and medical technology industries. It is reasonable to assume that it could also be compatible with the welded chain industry. There are still many shortcomings, and much research and development is still required to produce a versatile system. The following areas are in need of improvement if NDE is to become more widely accepted, and accurate enough to perform the tasks required:

- Detection of corrosion beneath paint and other coatings.
- Improved ultrasonic imaging
- Measurement of residual stresses below the materials surface.
- Detection of an evaluation of defects in complex geometric shapes, such as those encountered at the stud junction in a chain link.

It would also be very useful to determine mechanical properties of materials by NDE, such as tensile, yield, and fracture strengths, as well as ductility and fracture toughness. To do this would require the capability to detect pre-yield dislocation motion, residual stress, grain size, shape and distribution of inclusions in the material. At present, this evaluation is beyond the capabilities of even the most sophisticated testing procedures so far developed.

Even though there has been a great trend toward the automation of NDE, we are still very much dependent upon human interpretation of the test results. It is still difficult to identify good technicians, train them and have them perform well under certain conditions. More time should be spent in developing these inspection traits since even with the possibility that much of the inspection of the future will be conducted by machinery, there will always be a need for a good technician to make a final evaluation in special situations. These inspectors need more training than merely being able to perform NDT, since interpretation of the data is the most important factor in NDE. A good understanding of material properties and theory is essential in being able to make an evaluation as to the service life expectancy or economic repair value of a material. NDE has its shortcomings, especially when faced with parts having complex geometries, and it may not answer all the material questions that exist, but it is making studies in the right direction.

All the quality and reliability that is built into an anchor chain can be rapidly degraded if the chain is not properly maintained. For this reason, it is essential that all chain be regularly cleaned and refinished to reduce the corrosive action of a sea environment. In combination with this maintenance, other inspections should be conducted to ensure that the chain is not being overly strained or subjected to excessive wear conditions. Handling and stowage of anchor chain inflict some damage and these areas should be further investigated. Many NDT methods were cited as possible methods of conducting chain inspections, but field examination is still a very difficult task which produces results that show wide ranges of values.

Within the area of chain maintenance should be included all the associated equipment, such as the anchor windlass and controls. Since all these parts work together to produce the ship's mooring system, it is imperative that they function correctly together. Failure reports have shown that windlass and connecting link failures have resulted in the majority of mooring failures, so concentration on the maintenance of these components could be quite beneficial. The system analysis approach must be applied to solving failure problems. Looking at improving the quality of the anchor chain does very little if the main fault is within the connecting links or shackles.

Further studies should be conducted to investigate the interactions between chain, windlass, fairlead, anchor and other components. Dynamic loading models should be developed to study the actual loading conditions of the chain. Stress concentration locations should be identified in connecting links, and either eliminated or redesigned. The system must work properly as a whole, and the remaining components reliability must approach that of the chain. No gains can be made by improving welded chain link quality if the system will still fail due to another weak component.

APPENDIX A

Main Heat Conduction Program

```
C       PROGRAM HEATCON
C
C       FLASHBUTT WELDING HEAT FLOW MODELING PROGRAM
C
C            THIS PROGRAM IS AN ANALYTICAL SOLUTION OF THE HEAT CONDUCTION
C       PROCESS OCCURING IN FLASH-BUTT WELDED ANCHOR CHAIN. THE HEATING OF
C       THE ABUTTING SURFACES IS MODELED AS AN INSTANTANEOUSLY APPLIED PLA-
C       NAR HEAT SOURCE, MOVING AT CONSTANT VELOCITY OR CONSTANT ACCELERA-
C       TION. MATERIAL PROPERTIES ARE CONSIDERED CONSTANT OVER THE TEMPERA-
C       TURE RANGE OF THE WELDING PROCESS(1500-2800F).
C
C
        COMMON/CONST/U,TD,PI,G,FINAL,X(100),I,J,TIME(10000),T(10),D(10),DI
        DIMENSION TEMP(10000)
        EXTERNAL FCTL
        EXTERNAL FCTP
        INTEGER QQ
        ST = 0.
        G = 0.
        U = 0.
        XN = 0.
        RHO = 0.
        CK = 0.
        C = 0.
C       START TIME(ST) FOR THE FLASHING IS ALWAYS TAKEN AS ZERO SECONDS
C
        WRITE( 6,10)
C
   10   FORMAT(5X,'ENTER 0 IF LINEAR FLASHING PATTERN IS
        1DESIRED',/,5X,'ENTER 1 IF A PARABOLIC FLASHING PATTERN IS
        1DESIRED',/,25X,'FORMAT FOR INPUT IS (I1)'//)
C
        READ(5,20) IND
   20   FORMAT (I1)
        IF(IND.EQ.1) GO TO 35
        WRITE(6,25)
C
   25   FORMAT(5X,'ENTER CONSTANT VELOCITY U (IN/SEC) (F6.3)'//)
C
        READ (5,30) U
C
   30   FORMAT(F6.3)
C
        GO TO 48
C
   35   WRITE(6,40)
C
   40   FORMAT(5X,'ENTER CONSTANT ACCELERATION G (IN/SEC**2) (F6.3)'//)
C
        READ(5,45) G
C
   45   FORMAT(F6.3)
```

```
C
  48      WRITE(6,56)
C
  56   FORMAT(5X,'ENTER 10 TEMP. VALUES(DEG(F))(10F6.0)',//)
C
       READ(5,57)(T(I),I= 1, 10)
C
  57   FORMAT(10F6.0)
C
       WRITE(6,58)
C
  58   FORMAT(5X,'ENTER 10 THERMAL DIFFUSIVITIES(IN**2/SEC)(10F5.3)',//)
C
       READ(5,59)  (D(I), I=1,10)
C
  59   FORMAT  (10F5.3)
C
       WRITE(6,60)
C
  60   FORMAT(5X,'ENTER TEMPERATURE PARAMETERS:',/,15X,'TI = MATERIAL
     1 INITIAL TEMPERATURE(DEG(F))',/,15X,'TM = MELTING TEMPERATURE OF
     2 MATERIAL(DEG(F))',/,15X,'INPUT IN FORMAT(2F8.2)'//)
C
       READ(5,65) TI,TM
C
  65   FORMAT(2F8.2)
C      CALCULATE TEMPERATURE DIFFERENCE BETWEEN INITIAL AND INTERFACE.
C
       TD = (TM - TI)
C
       WRITE(6,69)
C
  69   FORMAT(5X,'CAUTION!!!..FINAL/STEP MUST BE LESS THAN 10000'//)
C
       WRITE(6,70)
C
  70   FORMAT(5X,'ENTER TIME PARAMETERS:',/,15X,'FINAL = MAX TIME FROM
     1 START OF FLASHING(SEC)',/,15X,'STEP=TIME INCREMENT OF INTEREST
     2 (SEC)',/,15X,'INPUT IN FORMAT(2F6.3)'//)
C
       READ(5,75) FINAL,STEP
C
  75   FORMAT(2F6.3)
C
       QQ = (FINAL/STEP)
C
       WRITE(6,80)
C
```

```
    80    FORMAT(5X,'ENTER FIELD SIZE PARAMETERS:',/,15X,'NN = NUMBER OF
         1DATA POINTS ALONG X-AXIS',/,15X,'XN=INITIAL POINT OF INTEREST
         2 ALONG X-AXIS(MIN XN = .01 (IN))',/,15X,'XSTEP = DISTANCE IN-
         3CREMENT (IN)',/,15X,'INPUT IN FORMAT(I3, 2F6.3)'//)
C
          READ(5,85) NN,XN,XSTEP
C
    85    FORMAT(I3, 2F6.3)
C
          WRITE(10,90)
C
          WRITE(6,90)
C
    90    FORMAT(5X,'ANALYTICAL SOLUTION OF A FLASH-BUTT WELDED ANCHOR
         1 CHAIN HEAT CONDUCTION',/,1X,'PROBLEM. THE HEAT SOURCE  WILL BE
         2 MODELED AS A PLANAR,MOVING,INSTANTANEOUSLY ',/,1X,'APPLIED
         3 SOURCE. DIFFUSIVITY IS INTERPOLATED FOR ACTUAL TEMPERATURE'//)
C
          IF(IND.EQ.1) GO TO 100
C
          WRITE (10,95)
C
          WRITE(6,95)
C
    95    FORMAT(5X,'THIS OUTPUT IS BASED UPON A LINEAR FLASHING
         1PATTERN (CONSTANT VELOCITY ',/,1X,'PLATEN MOTION) HEAT SOURCE.'
         2////)
C
          GO TO 110
C
   100    WRITE (10,105)
C
          WRITE (6,105)
C
   105    FORMAT(5X,'THIS OUTPUT IS BASED UPON A PARABOLIC FLASHING
         1 PATTERN ( CONSTANT ',/,1X,'ACCELERATION PLATEN MOTION) HEAT
         2 SOURCE.'////)
C
   110    WRITE(10,115) U, G, FINAL, STEP
C
          WRITE(6,115) U, G, FINAL, STEP
C
   115    FORMAT(5X,'WELDING PARAMETERS :',//,15X,'CONSTANT VELOCITY U='
         1,1X,F6.3,1X,'IN/SEC',//,15X,'CONSTANT ACCELERATION G=',1X,F6.3,
         21X,'IN/SEC**2',//,15X,'MAXIMUM TIME CONSIDERED (FINAL)=',1X,
         3F6.3,1X,'SEC.',//,15X,'TIME STEP INCREMENTS (STEP)=',1X,F6.3,1X,
         4'SEC.'////)
C
```

```
        WRITE(10,120) TI, TM
C
        WRITE(6,120) TI, TM
  120   FORMAT(5X,'MATERIAL PROPERTIES :',//,15X,'INITIAL TEMPERATURE
     1(TI) =',1X,F8.2,1X,'DEG(F)',//,15X,'MELTING TEMPERATURE(TM)=',
     21X,F8.2,1X,'DEG(F)'/////)
C
        WRITE(10,125) NN, XN, XSTEP
C
        WRITE(6,125) NN, XN, XSTEP
C
  125   FORMAT(5X,'FIELD SIZE PARAMETERS :',///,15X,'NUMBER OF X-AXIS
     1DATA POINTS (NN) =',1X,I3,//,15X,'INITIAL DISTANCE FROM WELD
     2INTERFACE (XN) =',1X,F6.3,1X,'INCHES',//,15X,'DISTANCE INCREMENT
     3 (XSTEP)=',1X,F6.3,1X,'INCHES'/////)
C
C       INTERACTIVE DATA INPUT IS COMPLETED
C
C       BEGIN THERMAL CALCULATIONS
C
C       **************** THERMAL DIFFUSIVITY=D(IN**2/SEC)****************
C
C
C
  127   WRITE(10,130)
C
        WRITE(6,130)
C
  130   FORMAT(5X,'TEMPERATURE(F)',5X,'THERMAL DIFFUSIVITY'//)
C
        WRITE(10,132) ((T(I),D(I)), I=1,10)
C
        WRITE(6,132)  ((T(I),D(I)), I=1,10)
C
  132   FORMAT(10X,F6.0,20X,F5.3,/)
C
        WRITE(10,135)
C
        WRITE(6,135)
C
  135   FORMAT(25X,'TEMPERATURE DISTRIBUTION OUTPUT',///)
C
        WRITE(6,140)
C
        WRITE(10,140)
C
  140   FORMAT(15X,'X = INSTANTANEOUS DISTANCE FROM FLASHING
     1   INTERFACE',///)
```

```
C
      TIME(1) = 0.
C
      PI = 3.14159
C
  145 DO 200 I = 1, NN
C
           X(I) = XN + (I-1)*(XSTEP)
C
           DO 160 J =2,QQ
C
                TO = TI
C
                TIME(J) = TIME(J-1) + STEP
C
                DI = D(4)
C
                TEMP(1) = TI
C
  147           IF(IND.EQ.1) GO TO 150
C
                CALL INTG((TIME(J-1)),(TIME(J)),FCTL,THETA)
C
                GO TO 155
C
  150           CALL INTG((TIME(J-1)),(TIME(J)),FCTP,THETA)
C
  155           TEMP(J) = TEMP(J-1) + THETA
C
                IF((TEMP(J)).GT.TM) TEMP(J) = TM
C
                IF((X(I)).EQ.0.) TEMP(J) = TM
C
                TC = TEMP(J)
C
                AB = ABS(TC-TO)
C
                IF(AB .LT. 5.)GO TO 160
C
                TA = (TO + TC)/2.
C
                TO = TC
C
                DI = FILLIN(TA,T,D,10)
C
                GO TO 147
C
  160      CONTINUE
```

```
C
               WRITE(10,165) (X(I))
C
               WRITE(6,165) (X(I))
C
 165           FORMAT(15X,'INSTANTANEOUS DISTANCE FROM INTERFACE=',F6.3,
   13X,'INCHES',//)
C
               WRITE(10,170)
C
               WRITE(6,170)
C
 170           FORMAT(25X,'(TIME)',6X,' (TEMP) ')
C
               WRITE(10,175) ((TIME(J), TEMP(J)), J =QQ,QQ)
C
               WRITE(6,175) ((TIME(J), TEMP(J)), J =QQ,QQ)
C
 175           FORMAT(25X,F6.3,2X,E12.5,///)
C
               WRITE(10,180)
C
               WRITE(6,180)
C
 180           FORMAT(2X,19('****'),//)
C
C
 200     CONTINUE
C
         WRITE(10,210)
C
         WRITE(6,210)
C
 210     FORMAT(5X,'TEMPERATURE OUTPUT IS COMPLETE')
C
 250     STOP
C
         END
C
         FUNCTION FCTL(TPRI)
C
         COMMON/CONST/U,TD,PI,G,FINAL,X(100),I,J,TIME(10000),T(10),D(10),DI
C
         C1 = 0.5*(U * TD)/SQRT(PI * DI)
C
         C2 = SQRT(FINAL - TPRI)
C
         C4 =(4.*DI*(FINAL-TPRI))
```

```
C
      C3=-((X(I))+((U/2.)*(FINAL-TPRI)))**2/C4
C
      IF (C3.LT.-160.) GO TO 10
C
      FCTL =(EXP(C3))*C1/C2
C
      RETURN
C
   10 FCTL= 0.0
C
      RETURN
C
      END
C
      FUNCTION FCTP(TPRI)
C
      COMMON/CONST/U,TD,PI,G,FINAL,X(100),I,J,TIME(10000),T(10),D(10),DI
C
      C4 = 0.5*(G * TD)/SQRT(PI*DI)
C
      C5= TPRI/SQRT(FINAL - TPRI)
C
      C6=-(((X(I))+((G/4.)*((FINAL**2)-(TPRI**2))))**2)
      C7= (4.)*DI*(FINAL-TPRI)
      C8=C6/C7
C
      IF ( C8.LT. -160.) GO TO 10
C
      FCTP = (EXP(C8))*C5*C4
C

      RETURN
C
   10 FCTP = 0.0
C
      RETURN
C
      END
C
      FUNCTION FILLIN(X,AB,OR,NO)
C
C     *** FILLIN *** PARABOLIC INTERPOLATION
C
C     FINDS Y(X) FROM A TABLE OF AB(N) AND OR(N) CONTAINING
C
C     NO POINTS.
C
```

```
      DIMENSION AB(NO),OR(NO)
      ANTRA(X1,X2,X3,X,Y1,Y2,Y3)=Y1*(X-X2)*(X-X3)/((X1-X2)*(X1-X3))+
     1 Y2*(X-X1)*(X-X3)/((X2-X1)*(X2-X3))+Y3*(X-X1)*(X-X2)/((X3-X1)*
     2 (X3-X2))
C
      IF(X-AB(1))    1,3,2
C
    3 Y=OR(1)
C
      GO TO 99
C
    1 Y=ANTRA(AB(1),AB(2),AB(3),X,OR(1),OR(2),OR(3))
C
      GO TO 99
C
    2 IF(X-AB(2)) 1,6,5
C
    6 Y=OR(2)
C
      GO TO 99
C
    5 DO 7 I=3,NO
C
      M=I
C
      IF(X-AB(I))8,9,7
C
    9 Y=OR(I)
C
      GO TO 99
C
    7 CONTINUE
C
    8 Y=ANTRA(AB(M-2),AB(M-1),AB(M),X,OR(M-2),OR(M-1),OR(M))
C
   99 FILLIN=Y
C
      RETURN
C
      END
```

Integration Subroutine

```
        SUBROUTINE INTG(ST,FINT,FCT,THETA)
C
C       PURPOSE:
C            TO COMPUTE THE INTEGRAL (FCT(TIME)) SUMMED OVER TIME FROM THE
C       INITIATION OF FLASHING TO THE FINAL TIME, AT VARIOUS X-AXIS LOCATIONS.
C
C       USAGE:
C            CALL INTG(ST,FINT,FCT,THETA)
C            PARAMETER FUNCTION REQUIRES AN EXTERNAL STATEMENT.
C
C       DESCRIPTION OF PARAMETERS:
C            ST=LOWER TIME OF THE INTERVAL
C            FINT=UPPER TIME OF THE INTERVAL(T-PRIME)
C            FCT=NAME OF THE EXTERNAL FUNCTION SUBPROGRAM USED
C            THETA=TEMPERATURE DIFFERENCE AT PARTICULAR TIME AND LOCATION
C
C       METHOD:
C            EVALUATION IS DONE BY MEANS OF A 10-POINT GAUSS QUADRATURE FORMULA
C            WHICH INTEGRATES POLYNOMIALS UP TO DEGREE 19 EXACTLY.
C
C
C
C******************************************************************************
C
C
        A = .5*(FINT + ST)
C
        B = (FINT - ST)
C
        E = .4869533 * B
C
        THETA = .03333567*(FCT(A+E) +FCT(A-E))
C
        E = .4325317 * B
C
        THETA = THETA + .07472567 * (FCT(A+E) + FCT(A-E))
C
        E = .3397048 * B
C
        THETA = THETA + .1095432 *(FCT(A+E) + FCT(A-E))
C
        E = .2166977 * B
C
        THETA = THETA + .1346334 *(FCT(A+E) + FCT(A-E))
C
        E = .07443717 * B
C
        THETA = B * (THETA + .1477621*(FCT(A+E) + FCT(A-E)))
C
        RETURN
C
        END
```

Sample Program Output

```
    ANALYTICAL SOLUTION OF A FLASH-BUTT WELDED ANCHOR   CHAIN HEAT CONDUCTION
PROBLEM. THE HEAT SOURCE  WILL BE        MODELED AS A PLANAR,MOVING,INSTANTANEOU
APPLIED  SOURCE. DIFFUSIVITY IS INTERPOLATED FOR ACTUAL TEMPERATURE


    THIS OUTPUT IS BASED UPON A PARABOLIC FLASHING  PATTERN ( CONSTANT
ACCELERATION PLATEN MOTION) HEAT SOURCE.



    WELDING PARAMETERS :

              CONSTANT VELOCITY U=  0.000 IN/SEC

              CONSTANT ACCELERATION G=  0.020 IN/SEC**2

              MAXIMUM TIME CONSIDERED (FINAL)=  9.490 SEC.

              TIME STEP INCREMENTS (STEP)=  0.010 SEC.



    MATERIAL PROPERTIES :

              INITIAL TEMPERATURE(TI) =   400.00 DEG(F)

              MELTING TEMPERATURE(TM)=  2750.00 DEG(F)



    FIELD SIZE PARAMETERS :

              NUMBER OF X-AXIS DATA POINTS (NN) =   1

              INITIAL DISTANCE FROM WELD INTERFACE (XN) =  0.150 INCHES

              DISTANCE INCREMENT (XSTEP)=  0.000 INCHES



    TEMPERATURE(F)      THERMAL DIFFUSIVITY

           80.                    0.025
```

```
                441.                        0.019

                801.                        0.014

               1161.                        0.009

               1341.                        0.005

               1385.                        0.003

               1431.                        0.006

               1701.                        0.009

               2061.                        0.011

               2750.                        0.014
                          TEMPERATURE DISTRIBUTION OUTPUT


                X = INSTANTANEOUS DISTANCE FROM FLASHING   INTERFACE


                INSTANTANEOUS DISTANCE FROM INTERFACE= 0.150   INCHES

                          (TIME)       (TEMP)
                           9.480    0.16045E+04


*****************************************************************************

  TEMPERATURE OUTPUT IS COMPLETE
```

```
    ANALYTICAL SOLUTION OF A FLASH-BUTT WELDED ANCHOR   CHAIN HEAT CONDUCTION
PROBLEM. THE HEAT SOURCE  WILL BE       MODELED AS A PLANAR,MOVING,INSTANTANEOU
APPLIED  SOURCE. DIFFUSIVITY IS INTERPOLATED FOR ACTUAL TEMPERATURE


    THIS OUTPUT IS BASED UPON A PARABOLIC FLASHING  PATTERN ( CONSTANT
ACCELERATION PLATEN MOTION) HEAT SOURCE.



    WELDING PARAMETERS :

              CONSTANT VELOCITY U=  0.000 IN/SEC

              CONSTANT ACCELERATION G=  0.020 IN/SEC**2

              MAXIMUM TIME CONSIDERED (FINAL)=  9.490 SEC.

              TIME STEP INCREMENTS (STEP)=  0.010 SEC.



    MATERIAL PROPERTIES :

              INITIAL TEMPERATURE(TI) =   800.00 DEG(F)

              MELTING TEMPERATURE(TM)=  2750.00 DEG(F)



    FIELD SIZE PARAMETERS :

              NUMBER OF X-AXIS DATA POINTS (NN) =   1

              INITIAL DISTANCE FROM WELD INTERFACE (XN) =  0.150 INCHES

              DISTANCE INCREMENT (XSTEP)=  0.000 INCHES



    TEMPERATURE(F)     THERMAL DIFFUSIVITY

          80.                    0.025
```

```
          441.                    0.019

          801.                    0.014

         1161.                    0.009

         1341.                    0.005

         1385.                    0.003

         1431.                    0.006

         1701.                    0.009

         2061.                    0.011

         2750.                    0.014
                      TEMPERATURE DISTRIBUTION OUTPUT


           X = INSTANTANEOUS DISTANCE FROM FLASHING   INTERFACE


           INSTANTANEOUS DISTANCE FROM INTERFACE= 0.150   INCHES

                       (TIME)       (TEMP)
                        9.480   0.16183E+04


****************************************************************************

   TEMPERATURE OUTPUT IS COMPLETE
```

```
    ANALYTICAL SOLUTION OF A FLASH-BUTT WELDED ANCHOR   CHAIN HEAT CONDUCTION
PROBLEM. THE HEAT SOURCE  WILL BE       MODELED AS A PLANAR,MOVING,INSTANTANEOU
APPLIED  SOURCE. DIFFUSIVITY IS INTERPOLATED FOR ACTUAL TEMPERATURE

    THIS OUTPUT IS BASED UPON A PARABOLIC FLASHING  PATTERN ( CONSTANT
ACCELERATION PLATEN MOTION) HEAT SOURCE.-


    WELDING PARAMETERS :

              CONSTANT VELOCITY U=  0.000 IN/SEC

              CONSTANT ACCELERATION G=  0.020 IN/SEC**2

              MAXIMUM TIME CONSIDERED (FINAL)=  9.490 SEC.

              TIME STEP INCREMENTS (STEP)=  0.010 SEC.


    MATERIAL PROPERTIES :

              INITIAL TEMPERATURE(TI) =  1550.00 DEG(F)

              MELTING TEMPERATURE(TM)=  2750.00 DEG(F)



    FIELD SIZE PARAMETERS :

              NUMBER OF X-AXIS DATA POINTS (NN) =  10

              INITIAL DISTANCE FROM WELD INTERFACE (XN) =  0.050 INCHES

              DISTANCE INCREMENT (XSTEP)=  0.050 INCHES



    TEMPERATURE(F)      THERMAL DIFFUSIVITY

          80.                     0.025
```

```
          441.                    0.019

          801.                    0.014

         1161.                    0.009

         1341.                    0.005

         1385.                    0.003

         1431.                    0.006

         1701.                    0.009

         2061.                    0.011

         2750.                    0.014
                          TEMPERATURE DISTRIBUTION OUTPUT


            X = INSTANTANEOUS DISTANCE FROM FLASHING   INTERFACE


            INSTANTANEOUS DISTANCE FROM INTERFACE= 0.050   INCHES

                          (TIME)        (TEMP)
                           9.480   0.27500E+04


*************************************************************************

            INSTANTANEOUS DISTANCE FROM INTERFACE= 0.100   INCHES

                          (TIME)        (TEMP)
                           9.480   0.23391E+04


*************************************************************************
```

```
            INSTANTANEOUS DISTANCE FROM INTERFACE= 0.150   INCHES

                      (TIME)        (TEMP)
                       9.480    0.20339E+04

*****************************************************************************

            INSTANTANEOUS DISTANCE FROM INTERFACE= 0.200   INCHES

                      (TIME)        (TEMP)
                       9.480    0.18622E+04

*****************************************************************************

            INSTANTANEOUS DISTANCE FROM INTERFACE= 0.250   INCHES

                      (TIME)        (TEMP)
                       9.480    0.17638E+04

*****************************************************************************

            INSTANTANEOUS DISTANCE FROM INTERFACE= 0.300   INCHES

                      (TIME)        (TEMP)
                       9.480    0.16912E+04

*****************************************************************************

            INSTANTANEOUS DISTANCE FROM INTERFACE= 0.350   INCHES

                      (TIME)        (TEMP)
```

```
                        9.480   0.16410E+04

*****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.400   INCHES

                       (TIME)       (TEMP)
                        9.480   0.16078E+04

*****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.450   INCHES

                       (TIME)       (TEMP)
                        9.480   0.15862E+04

*****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.500   INCHES

                       (TIME)       (TEMP)
                        9.480   0.15721E+04

*****************************************************************************

   TEMPERATURE OUTPUT IS COMPLETE
```

```
    ANALYTICAL SOLUTION OF A FLASH-BUTT WELDED ANCHOR   CHAIN HEAT CONDUCTION
PROBLEM. THE HEAT SOURCE  WILL BE        MODELED AS A PLANAR,MOVING,INSTANTANEOU
APPLIED  SOURCE. DIFFUSIVITY IS INTERPOLATED FOR ACTUAL TEMPERATURE


    THIS OUTPUT IS BASED UPON A LINEAR FLASHING PATTERN (CONSTANT VELOCITY
PLATEN MOTION) HEAT SOURCE.



    WELDING PARAMETERS :

              CONSTANT VELOCITY U=  0.144 IN/SEC

              CONSTANT ACCELERATION G=  0.000 IN/SEC**2

              MAXIMUM TIME CONSIDERED (FINAL)=  8.250 SEC.

              TIME STEP INCREMENTS (STEP)=  0.010 SEC.



    MATERIAL PROPERTIES :

              INITIAL TEMPERATURE(TI) =  1550.00 DEG(F)

              MELTING TEMPERATURE(TM)=  2750.00 DEG(F)




    FIELD SIZE PARAMETERS :


              NUMBER OF X-AXIS DATA POINTS (NN) =  10

              INITIAL DISTANCE FROM WELD INTERFACE (XN) =  0.050 INCHES

              DISTANCE INCREMENT (XSTEP)=  0.050 INCHES




    TEMPERATURE(F)      THERMAL DIFFUSIVITY

          80.                   0.025
```

```
      441.                      0.019

      801.                      0.014

     1161.                      0.009

     1341.                      0.005

     1385.                      0.003

     1431.                      0.006

     1701.                      0.009

     2061.                      0.011

     2750.                      0.014
                    TEMPERATURE DISTRIBUTION OUTPUT


        X = INSTANTANEOUS DISTANCE FROM FLASHING   INTERFACE


        INSTANTANEOUS DISTANCE FROM INTERFACE= 0.050   INCHES

                    (TIME)       (TEMP)
                     6.240   0.27500E+04


****************************************************************************

        INSTANTANEOUS DISTANCE FROM INTERFACE= 0.100   INCHES

                    (TIME)       (TEMP)
                     6.240   0.23937E+04


****************************************************************************
```

```
             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.150   INCHES

                       (TIME)       (TEMP)
                        6.240   0.20930E+04

****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.200   INCHES

                       (TIME)       (TEMP)
                        6.240   0.19020E+04

****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.250   INCHES

                       (TIME)       (TEMP)
                        6.240   0.17916E+04

****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.300   INCHES

                       (TIME)       (TEMP)
                        6.240   0.17101E+04

****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.350   INCHES

                       (TIME)       (TEMP)
```

```
                        6.240    0.18517E+04

*****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.400    INCHES

                       (TIME)        (TEMP)
                        6.240    0.16124E+04

*****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.450    INCHES

                       (TIME)        (TEMP)
                        6.240    0.15870E+04

*****************************************************************************

             INSTANTANEOUS DISTANCE FROM INTERFACE= 0.500    INCHES

                       (TIME)        (TEMP)
                        6.240    0.15709E+04

*****************************************************************************

   TEMPERATURE OUTPUT IS COMPLETE
```

APPENDIX B

Case Studies of Welded Chain Failures

One of the major problems encountered in trying to determine the causes of welded chain failure is the lack of documentation of the actual chain failures. The number of documented case studies compared to the number of failures is quite small and may not numerically reflect the true representation of the frequency of occurence of the particular types of failure. The U.S. Navy maintains a good reporting system, but since welded chain has not been extensively used, only limited case studies are available. Of the case studies that exist, many were reported by shipboard personnel and reflect a failure analysis from an operator's viewpoint.

The world's merchant fleets are not always required to document their casualties, and for this reason the number of case studies of failure analysis is very small. Even the documented cases are often vague and fail to identify the type of chain, material properties (i.e., toughness), loading conditions, and method of stud insertion. For these reasons, it becomes very difficult to judge why certain failures occured when insufficient information exists to make an engineering decision. A need therefore exists to document all anchor chain casualties, so that the dominant causes of failure can be identified and corrected where possible. Failures associated with the fabrication process could possibly be decreased by the improvement of manufacturing techniques and quality control. A literature search has revealed several case studies of chain failure and some of these will be discussed. Again these are only a sampling of types of failure that can occur, and may not reflect all of the possible methods of failure.

TABLE OF
CHAIN FAILURE ANALYSIS

CAUSE OF CHAIN FAILURE	INFLUENCE ON FAILURE RATE*
Lack of Fusion	Very Significant
Hot Cracking	
Electrode/Grip Defects	
Corrosion	Significant
Brittle Failure	
Notch Initiated	
Wear and Abuse	Marginal/ Undetermined
Fatigue	

* Author's Priority Listing

CASE 1

Investigation of Worn Chain Links

Several links of chain showing excessively high wear were examined by Naumann and Spies.(63) Their investigation dealt with flash welded chain that was end-welded, but the results are of general interest. The area of heaviest wear occured at the bend in the link (weld) which corresponds to an area of high stress. A metallographic examination was made of this area, and also sections of the undamaged area were studied. The results revealed that the outer surface of the chain link contained coarse acircular martensite with a fairly large percentage of retained austenite, all indications of the link being strongly overheated.

Additionally, it was noted that the butt weld seams were not of extremely high quality, and were covered with oxide inclusions. These inclusions could have resulted from insufficient upsetting distance during fabrication. Because of the poor weld quality, this area understandably exhibited an extremely high wear-rate with respect to the rest of the chain link area. From this case study, it can be seen that the initial appearance of an excessive wear pattern could be misleading in that the real problem was caused by overheating and insufficient upsetting action.

CASE 2

Fractured Chain Link

A second chain failure studied by Naumann and Spies(63) involved a link of a heat resistant steel 30 Cr Mo V9 chain. The actual fracture surface had a conchoidal structure and followed the austenitic grain boundaries, which is an indication of overheating. The reason for the fracture following the grain boundaries is because many of the sulfidic and oxydic impurities are slightly soluble and upon cooling, deposit along the grain boundaries as a fine dispersion. Because these oxides degrade the material quality, they lower the strength and plasticity of the steel. This decrease in plasticity is of particular importance in chain links since it can give rise to premature appearance of a fracture attributable to low ductility. Confirmation of the suspicion of overheating was gained by the detection of a coarse-grained acircular heat-treated structure of the chain link. The chain had to have been overheated to a fairly high temperature (i.e., greater than 2100°F), in order for the impurities to dissolve.

CASE 3

Failure of Electrically Butt-Welded Mild Steel Chains

In a chain failure study compiled by Hutchings$^{(64)}$ of a studless welded chain link, the failure resulted from fracture of one of the links in the plane of the weld. Other links of the same chain exhibited cracking within the weld area, with the apparent crack initiation sites being the inner link surface. Samples were taken from the weld area, and the results revealed the presence of discontinuities caused by lack of fusion or inadequate expulsion of the oxides formed. Additionally, the theory of inadequate fusion was substantiated by the presence of a pearlite structure in the area next to the discontinuities.

The final evaluation was that the failures were due to defective chain produced by an automatic welding machine. Since several of the links tested gave the same indications, it was concluded that the initial machine settings were improper, or that the welding parameter settings had drifted off their set position over a period of time. This type of failure was not uncommon, since a large number of examples were encountered. The conclusion of this study was that the only means to avoid these defects was to ensure that proper settings were maintained on the welding machines. Frequent testing, inspection and checking of the weld quality was necessary to keep defective chains from entering active service.

CASE 4

Fatigue Failures of Links from Grab Chains(64)

The chain studied in this case was studless, and produced from higher tensile steel. Failure of the link occured at a location adjacent to the butt weld in the side of the link after a service life of about six months. The fracture surface exhibited two distinct areas:

1) Bright crystalline - area resulting from brittle fracture at the time of failure.

2) Discolored, dark - area associated with earlier existing fatigue crack (crack initiation area).

A concurrent failure occured at the crown, which resulted from a combined brittle rupture and tearing action.

Microscopic investigation revealed that the butt welds were of good quality, but the failure initiated within the HAZ of the weld (.0625 in.). A further examination indicated that numerous surface fissures existed, which could have been present in the bar stock, or could have resulted from the repeated stresses of in-service use. These fissures had the appearance of corrosion-fatigue, or fatigue cracks, but this could not be definitively determined. Surface decarburization was also present, which indicated that the chain was improperly normalized or that the bar stock was initially at fault.

The conclusions drawn on this particular failure were that one of the surface fissures developed a high growth rate, and when it reached approximately mid-section there was insufficient metal area available to withstand the applied load. Possibly due to a suddenly applied load or shock, the chain failed in a brittle manner. Further inspection of other chain links revealed that similar fatigue cracks existed in numerous other links, thereby indicating that other failure sites also existed and that the failed link was not just an isolated case.

CASE 5

Fatigue Failure(64)

A failed link of studless, high tensile strength steel chain was examined, and it was determined that fracture took place in an area adjacent to the side butt weld joint. Within the fracture area three specific zones were detected:

1. Smooth fracture - approximately half the cross-sectional area was composed of this, extending from the inside of link and extending to about half the thickness of the bar diameter. Because of the nature of this surface it was concluded that this area of fracture was due to the gradual growth of fatigue cracking.
2. Coarse fracture - about 75% of the remaining area (30% of entire chain rod diameter) exhibited this coarser fracture surface. The coarser structure was associated with a more rapid crack growth rate and hence the time to cover this area was considerably less than that of the previous zone. This area was located adjacent to,and outboard of, the smooth fracture zone.
3. Tear zone - this area encompassed about 20% of the entire rod diameter and was caused by a rapidly propagating crack which had exceeded

the critical crack length of the material. This area tore out at the time of final failure.

Closer microscopic examination revealed that the actual failure occurred in the HAZ, where grain refinement took place during welding, fairly close to the weld line. The weld itself was of good quality, and there were no indications of decarburization or oxide inclusions. A study of the link contour indicated that a slight physical surface depression existed at the sight of the crack initiation. The appearance of the crack was identified as being typical of one resulting from fatigue action.

Several other links from the chain were examined and additional cracks were identified in the areas of the weld line. Some of these defects were fissures associated with the oxidized material that had been partially expelled from the weld line during the upsetting action. The presence of the oxides indicates possible overheating during the welding process. Since these oxides were located only on the outside surfaces of the link, and this is usually trimmed off after the upsetting stage, it implied that inadequate trimming had taken place. The cracks that did cause failure all started in the upset portion of the joint, with the cracks situated in the HAZ where the material was subjected to a transition temperature range. In this zone, some material is heated above its critical temperature while at the other end of the zone the material is virtually unaffected. It was concluded that this transition zone was associated with a slight degradation of the material's fatigue endurance and other mechanical properties. This change in properties could have caused a "mechanical notch", which acted as a stress concentration factor for crack initiation and growth, resulting in failure of the link.

CASE 6

Failure of 3½" Chain Cable Links

A chain failure analysis of 3½ in. anchor chain (CRQ) conducted by Lloyd's Register of Shipping[(65)] revealed that the broken links failed in a brittle manner at the positions of the flash butt welds, and at similar positions at the other sides of the link. The initial fracture was caused by hot cracking in the butt welds. Further tests showed that the chain material exhibited inadequate impact strength at 32°F. Steels of the type from which this particular chain was made, 1.6 - 1.9% Manganese, could develop partially hardened surfaces upon normalizing. This characteristic is dominant if the amount of manganese is present close to its upper limit.

The fractures that occurred in the vicinity of the weld line showed a black oxidized area on that part of the fracture adjacent to the stud. A coarse granular structure was noted, along with a high temperature scale coating. In the area away from the stud interface the fracture was bright in appearance and crystalline, indications of brittle fracture. It should be noted that the fractures on the opposite sides of the link (away from weld) were entirely brittle in nature. The characteristic chevron markings indicated the origins to be positions where the studs were circumferentially arc welded to the link. (These fracture sites may have been induced by the stop-start action of welding in the stud.) These brittle fractures at the welded stud interface were transgranular and had propagated from shallow weld deposits between the links and the ends of the studs.

The final conclusion was drawn that the tendency for carbon steels with manganese content greater than 1.5% to exhibit air hardening with drastic notch ductility reduction should be anticipated. When the Mn content approaches 2% other elements such as nickel, and chromium tend to be fairly high and, hence, increase the possibility of partial hardening of the steel. It is therefore recommended that the chain be tempered after the normalization process in order to restore its toughness.

CASE 7

Examination of Defective 3¼ in. Chain

A chain link from a chain used on a drilling rig failed due to hot cracks in the overheated zones on both sides of the flash butt weld. This investigation conducted by Lloyd's(66) showed that the bar stock had met tensile requirements, but exhibited insufficient toughness. The low impact strength was associated with the presence of a bainite structure, which had formed due to the Manganese content of 1.93%.

The site of the actual failure contained a ground groove which had a small crack in its bottom section. The lower part of this crack was oxidized and scaled, and similar conditions were found on the fracture closer to the position of the stud. In addition, a dark line defect on the weld fusion line was confirmed to be a discontinuity in the weld. It contained entrapped scale and oxide.

The overall conclusion was that the major defects in the weld zone were hot cracks associated with the severe grain coarsening experienced by the HAZ microstructure caused by overheating during welding. Even though the chain had been correctly normalized, which was confirmed by the uniform material hardness and structure, this could not compensate for the damage caused during overheating. The problem was further complicated by the presence of the bainite structure which lowered the notch toughness of the chain link.

CASE 8

Broken Chain Cable

Another case study conducted by Lloyd's (67) deals with an anchor chain that suffered a transverse fracture that occurred through the center of the indentation caused by the stud. The area immediately below the stud was crystalline in nature and covered with a dark scale associated with hot cracking of the butt weld. The lower half of the fracture was clearly the result of brittle fracture due to the presence of chevron markings on the fracture surface. Macroscopic examination of link sections revealed the presence of a flash-butt weld in the center of a severe indentation produced during fitting of the stud link, which resulted in fracture along the HAZ.

The investigation concluded that the brittle failure was caused by a crack in the weld zone that was present prior to the chain being placed in service. This was substantiated by the heavy decarburization of the fracture surfaces of the original crack, indicating its presence prior to final heat treatment. Since the fracture did not originate on the flash weld line, it was concluded that the initial flaw was caused during the closing of the link into the stud. The pressure applied during this operation caused local indentation and flattening of the stud, resulting in a longitudinal strain. This plastic deformation caused the initial crack which was the origin of the final fracture.

CASE 9

Examination of Cracked 3½ in. Chain

This Lloyd's study investigated circumferential cracking from the center lines of the flash butt welds.(68) These particular chains did not fail, but were rejected during magnetic particle inspection. The cracks were crescent shaped laps on the link surface, and they were present on both sides of the weld line (about 1 inch). The material contained some bainite which accounted for its lower than expected notch toughness.

The flash butt welds of all the links were sound, and the HAZ structures were reasonably fine grained. The disturbed nature of the flow pattern of the steel indicated they were folds in the surfaces of the links which penetrated up to .3 inches. Because of the nature of the defect, and because of its constant location, it was concluded that they were associated with the method of gripping the bars during the flash-butt welding process. This is reasonable since similar problems have been encountered in the production of continuous welded rails for the railroad industry. Another cause of failure associated with the grips/electrodes, reported by the rail industry, has been localized burning, which has led to many defective rails.

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