SSC-198

FLAME STRAIGHTENING AND ITS EFFECT ON BASE METAL PROPERTIES

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AUGUST 1969

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August 1969

Dear Sir:

Fairing and straightening of ships' hull plates distorted by welding during fabrication or by damage during operations has been a problem for many years. Flame straightening methods found acceptable for mild steels were considered excessively detrimental to material properties of the high-strength steels in common use today. Project SR-185, "Straightening Distorted Weldments," was undertaken to determine the extent of deterioration of flame straightened plates and to develop alternative methods of distortion removal. The first portion of the project involved a literature survey. The accompanying report, "Flame Straightening and Its Effect on Base Metal Properties," by H. E. Pattee, R. M. Evans, and R. E. Monroe contains the information from that review.

This report has been distributed to individuals and groups associated with or interested in the work of the Ship Structure Committee. Comments concerning this report are solicited.

Sincerelv,

C. P. Murphy,
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-198

Summary Report

on

Project SR-185

"Straightening Distorted Weldments"

to the

Ship Structure Committee

FLAME STRAIGHTENING AND ITS EFFECT ON BASE METAL PROPERTIES

by

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Columbus, Ohio

under

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Naval Ship Engineering Center
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U. S. Coast Guard Headquarters
Washington, D. C.

August 1969

ABSTRACT

The suitability of flame-straightening methods now used on conventional ship steels for the higher strength ship steels is questionable. This report discusses some of the potential problem areas that need evaluation to examine this subject. Based on a survey of pertinent literature it is shown that only limited data applicable to this subject are available. The data analysis covered the nature of distortion, flame straightening techniques, and the effects of both single and combined thermal cycles and plastic strain cycles on material properties. An experimental program is presented that is designed to generate background data on conventional steels and several higher strength steels directly pertinent to flame straightening. These data will subsequently be evaluated to ascertain suitability of the flame-straightening procedure for various ship steels.

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Introduction

Distortion is a perennial problem in the shipbuilding industry, and much effort has been expended to minimize the distortion that occurs as the result of the fabrication procedures. While distortion can be produced by many of the assembly procedures used in ship fabrication, its principal cause today is welding. Welding is used extensively in modern shipbuilding yards, since it offers many advantages over other assembly methods. However, as with any complex structure, problems are encountered when ship hulls and structural sections are fabricated by welding. While distortion can be minimized and/or controlled by proper design of the weldment and careful selection of the welding process and welding variables, some inevitably occurs. When the amount of distortion exceeds acceptance limits, it must be removed.

There are three approaches to resolving the problem of weld distortion.

(1) Development of welding processes and fabrication procedures that minimize distortion

(2) Establishment of rational standards for acceptable limits of distortion

(3) Development of proper techniques for removing distortion that has already occurred.

A proper combination of these approaches will be most effective in controlling weld distortion in actual ship fabrication.

The first approach to reduction and control of weld distortion is to minimize distortion. It is much better to build a ship without distortion than to reduce distortion later. First of all, if we developed a welding process which reduced shrinkage and distortion for individual welds, distortion occurring during fabrication of a complex welded structure would also be reduced. Presently, however, there is no process which completely eliminates distortion. Accepting this fact, we can turn to the many factors within the welding procedure which contribute to the distortion of a large, complex structure such as a ship hull. These factors include welding sequence, degree of constraint, welding conditions, joint details, and preheat and interpass temperature. It is important to determine how these factors contribute to distortion. A large industrial group research program is currently in progress to investigate these factors. Special attention is being given to shipbuilding problems because many of the sponsors of this research are shipbuilding companies.

The second approach to controlling distortion accepts the fact that some amount of distortion inevitably occurs due to welding. Then, an important technical problem is to establish rational and practical standards for acceptable limits of distortion. The standards should be established on the basis of:

(1) The structural reliability of the ship

(2) The economic value of the ship

(3) Fabrication cost.

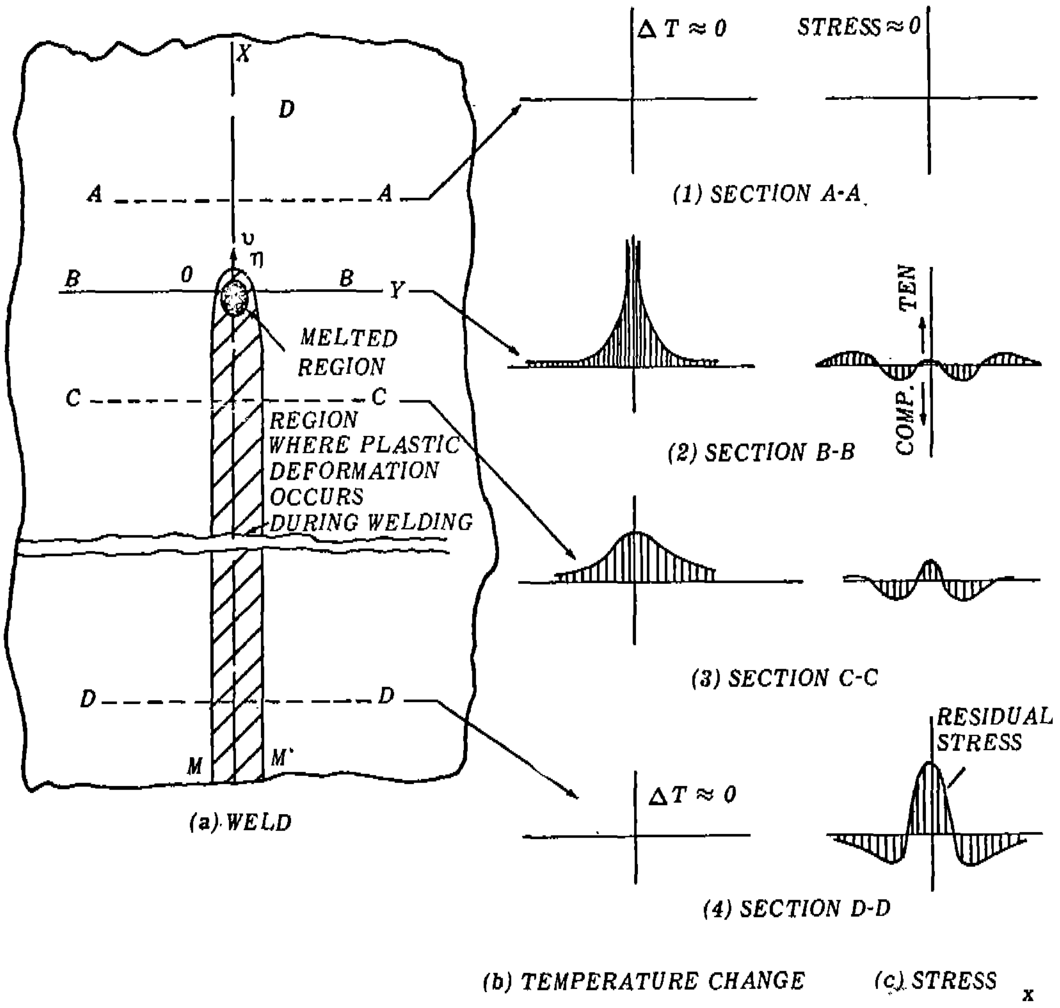


FIG. 1. Schematic Representation of Changes of Temperature and Stresses during Welding.

The effects of these dimensional changes on a simple butt weld are shown in Figure 2. Examples of distortion due to longitudinal shrinkage are shown in Figure 3. The amount and type of distortion that occurs in weldments such as those encountered in shipbuilding is much more complex than that shown in simple welded joints. In 1961 Kerr discussed the problem of distortion in shipbuilding.(1) Kerr indicated that a volumetric contraction of about 10 percent occurs in the cooling of the weld zone in mild steel. The liquid weld metal solidifies at about 2700 F. But it is highly plastic at this time. With decreasing temperature there is a progressive increase in strength of the weld metal until the temperature reaches about 1650 F; during this period the weld metal contracts and the stress level increases. Below 1650 F, the weld metal plasticity decreases and high stresses are present in the weld metal and surrounding metal; these stresses produce distortion in the weldment.

Such standards must be rational and practical so that any harmful distortion can be avoided while unharmful distortion is accepted to eliminate unnecessary rework. In regard to structural reliability, studies are needed to determine the adeqaacy of present tolerances. It is now possible to determine analytically the acceptable distortion of a member under given service conditions. It is also possible to determine the maximum weld size that will produce acceptable distortion when welds are made with normal procedures. There is considerable disagreement among shipbuilders and ship owners regarding the amount of distortion that can be tolerated from an economic viewpoint. Although distortion may not affect a ship's reliability, it may damage the appearance and thus reduce the ship's worth. A study, in which classification societies, government agencies, and ship owners are questioned, could be used to establish acceptable standards. Finally, extremely close distortion tolerances can result in extremely high fabrication cost. This is a factor that must be carefully weighed whenever distortion standards are established.

In fabricating ships with high-strength steels, especially heat-treated steels, it is important to minimize postweld straightening. We have discussed two ways of doing this. Nevertheless, distortion that exceeds the acceptable limits may occur. Distortion also may occur during service, say by collision. If this happens, methods are needed to remove the distortion economically with minimum damage to the structure. Many techniques have been used for removing distortion in a ship hull. Most commonly used techniques involve flame heating the plate on spots/or along lines, followed by cooling with water. Sometimes plates are beaten with a hammer while they are heated. However, these techniques are very much an art. Only limited scientific information, either analytical or experimental, is available on mechanisms of distortion removal or on material degradation due to these treatments.

This report primarily considers what is known currently about the effects of flame-straightening treatments on ship steels.

Nature of Distortion

Distortion in weldments is primarily the result of the combined effects of (1) locally-applied heat in the weld zone, and (2) restraint provided by the relatively cold metal on either side of the weld bead and by other members of the structure. Because a weldment is heated locally by the welding heat source, the temperature and stress distribution in the weldment is not uniform and changes as welding progresses (Figure 1). During the welding cycle, complex strains occur in the solidified weld metal and base metal regions near the weld during the heating and cooling cycles. The strains produced during heating may be accompanied by plastic upsetting. The stresses resulting from these strains combine and react to produce internal forces that cause bending, buckling, and rotation.

The distortion encountered in welded structures occur as the result of three fundamental dimensional changes during the welding process:

(1) Transverse shrinkage that occurs perpendicular to the weld
(2) Longitudinal shrinkage that occurs parallel to the weld
(3) Angular change that consists of rotation around the weld.

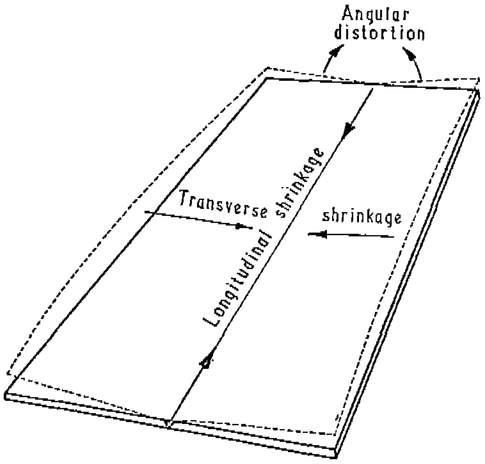
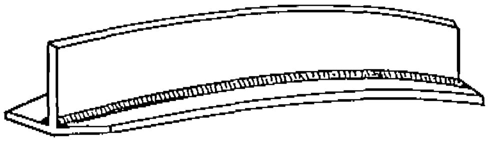
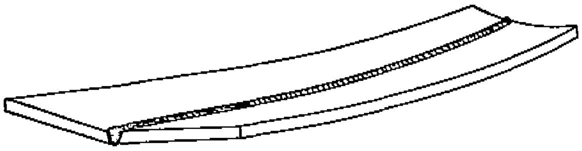


Fig. 2. Effects of Shrinkage, Causing Plates to Take Shape of Dotted Lines.



(a) LONGITUDINAL DISTORTION OF A BUILT-UP BEAM



(b) LONGITUDINAL BENDING DISTORTION OF A SINGLE-VEE BUTT WELD

(c) BUCKLING DISTORTION

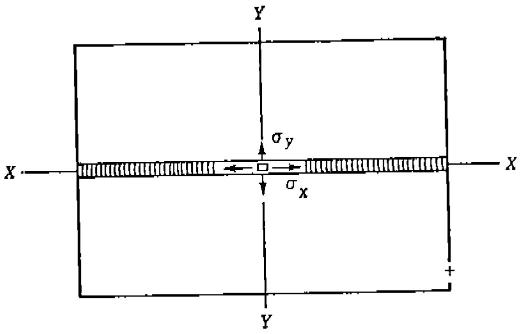
Fig. 3. Distortions Induced by Longitudinal Shrinkage.

A typical distribution of residual stresses in a butt weld is shown in Figure 4. The stresses of concern are those parallel to the weld direction, designated σ_x, and those transverse to the weld, designated σ_y.

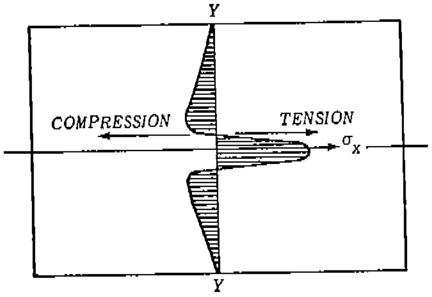
The distribution of the σ_x residual stress along a line transverse to the weld (YY) is shown in Figure 4 (b). Tensile stresses of high magnitude are produced in the region of the weld; these taper off rapidly and become compressive at a distance of several times the width of the weld. The weld metal and heat-affected zone try to shrink in the direction of the weld, and the adjacent plate material prevents this shrinkage. The distribution of σ_y residual stress along the length of the weld XX is shown by Curve 1 in Figure 4 (c). Tensile stresses of relatively low magnitude are produced in the middle of the joint, and compressive stresses are observed at the end of the joint.

If the contraction of the joint is restrained by an external constraint, the distribution of σ_y is as shown by Curve 2 in Figure 4 (c). Tensile stresses, approximately uniform along the weld, are added as the reaction stress. An external constraint, however, has little influence on the distribution of σ_x residual stresses.

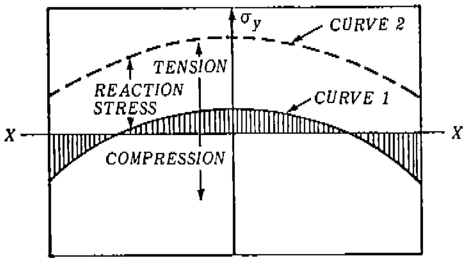
Comprehensive reviews on weld distortion and residual stresses have been prepared by Spraragen and associates.(2-4) Kihara and Masubuchi,(5,6) Wanatale and Satoh,(7) and Okerbloom.(8) These references should be consulted for further information on this subject.



(a) BUTT WELD



(b) DISTRIBUTION OF σ_x ALONG YY



(c) DISTRIBUTION OF σ_y ALONG XX

FIGURE 4. TYPICAL DISTRIBUTION OF RESIDUAL STRESSES IN BUTT WELD

Fig. 4. Typical Distribution of Residual Stresses in Butt Weld

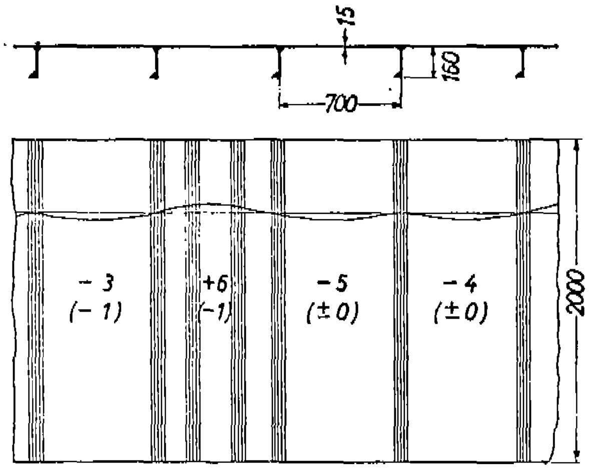
The methods used to correct unacceptable distortion are becoming increasingly a matter of concern to those who design and construct ships, because of the type of base metals being used. The high-strength, low-alloy steels are attractive from the standpoint of weight, strength, and cost; however they are far more sensitive to the affects of the straightening parameters than the previously used structural steels. The removal or correction of distortion is usually accomplished by (1) flame straightening, or by (2) heating the distorted area and straightening by mechanical means. While such methods have been used successfully for many years without concern, there is considerable question today in regard to the effect of the straightening parameters on the mechanical and metallurgical properties of high-strength base metals. The same concern is present with respect to aluminum which is being used increasingly for the fabrication of ship superstructures. The expressed concern has much basis in fact, particularly since there is little control of the straightening parameters. For the most part, straightening procedures are an art rather than a science.

Flame-Straightening Techniques

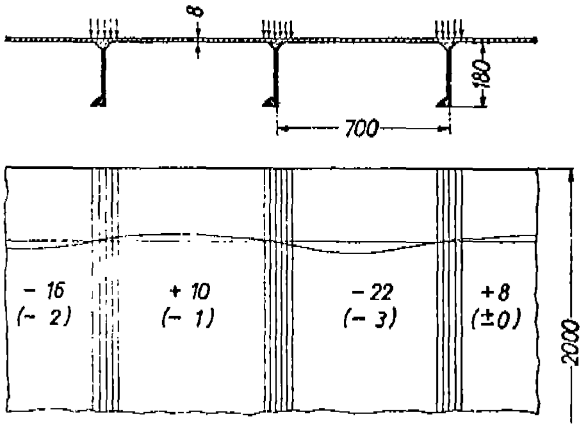
A brief review of the literature is included in this report to (1) provide background information on flame straightening procedures, (2) define problem areas that arise because of these operations, and (3) enumerate the variables that can influence base metal properties. The distortion in small parts can sometimes be corrected by placing the parts in a press and applying pressure; heat may or may not be required. Large structural sections such as those encountered in ships must be straightened in place. Flame straightening is a general term that is applied to most of these straightening operations, even though more than a flame may be involved. In some cases, an oxyacetylene torch is used to heat the distorted area until it reaches the desired temperature. Then heating ceases and this area is cooled to produce a controlled amount of shrinkage. While convection cooling is often used, the rate of cooling can be increased by spraying the heated area with water. Depending on the amount of distortion as well as the size and location of the distorted area, this procedure may have to be repeated several times to completely straighten the area. In other cases, the distorted area is heated with an oxyacetyline torch; then, auxiliary equipment is used to remove distortion by pressing, hammering, forging, etc. In addition to their use in the shipbuilding industry, these procedures are used widely in other industries for straightening purposes; they are also used in bending structural members to obtain a desired amount of curvature.

Numerous applications of flame straightening have been reported by Holt.(9-13) In 1955 the basic principles of flame straightening as applied to simple steel beams were discussed with particular emphasis on the effect of various heating patterns on the correction of distortion.(9-10) In subsequent articles, the details of flame straightening the structural members of a large fire-damaged hangar were reviewed.(11-12) Work of this nature is very similar to that encountered in ship fabrication, since it was necessary to straighten load-bearing members in place. An article on the fundamentals of flame straightening was published in 1965.(13) A temperature not exceeding 1200 F was recommended for straightening; higher temperatures can produce buckling and material property changes. Data were also presented on the amount of plastic flow that occurs when a conventional structural steel (A36) is heated to typical flame straightening temperatures.

Flame straightening applications in the shipbuilding industry have been discussed in detail by Bernard and Schulze.(14) Following a review of the fundamentals of this process and a discussion of the equipment used for straightening, several examples of ship structures that were flame straightened were discussed. Data are presented on the amount of distortion present in welded hull and deck sections before and after straightening (Figure 5). The differences in the heating patterns used to flame straighten thin (less than 0.400-inch-thick) and thick plate are reviewed; interrupted patterns appear to be most effective. While there is considerable information on the methods to apply restraint to heated sections, few data are provided on the straightening parameters, although the speed at which the torch is moved for heating is usually given. The heating or straightening temperature is specified as that which produces a "red glow" in the plate. A somewhat similar article on the use of flame straightening in the sheet metal industry was written by Pfeiffer.(15) This article contains considerable information on the special heating techniques and methods of applying pressure that are required to straighten thin sheet metal sections. Some of this information may be of use in ship fabrication where relatively thin plate is used.



a. Straightening of a Hull Section



b. Straightening of a Deck Section

Fig. 5. Flame Straightening of Distortion in Ship Fabrication(14)

Notes: (1) All dimensions are in millimeters (1 mm = 0.040 inch)

(2) Amount of distortion is indicated before and after ( ) straightening

(3) Flame heating path with 5-burner torches is indicated by series of closely spaced lines.

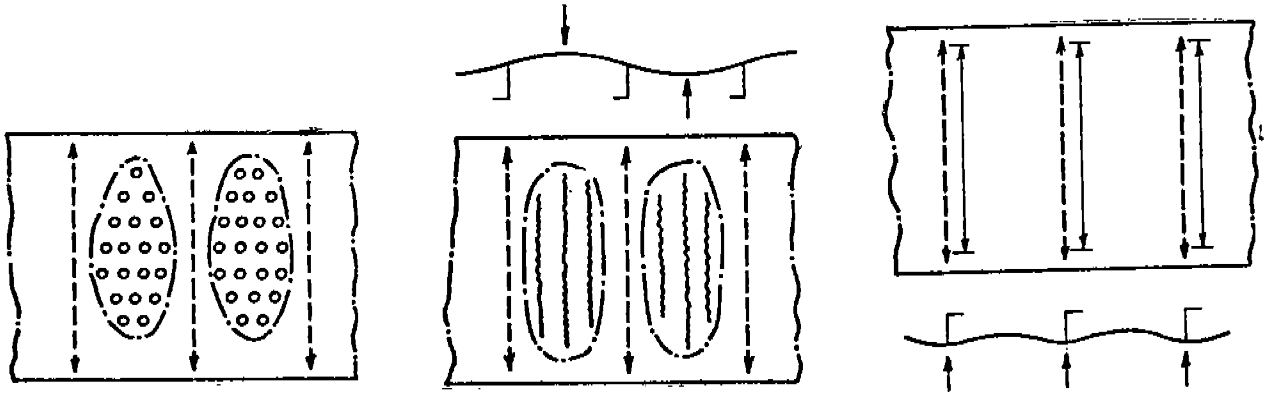
Flame straightening procedures have also been reviewed in the Soviet literature by Tsalman in 1959; this article is mostly concerned with the correction of distortion in welded structural members such as box beams, I-beams, and other assemblies.(16) Heating patterns and their effect in producing a controlled amount of reverse distortion in selected areas are discussed. The flame straightening temperatures ranged from 500 to 800 C (932 to 1472 F); the actual temperature to which the part was heated was determined mainly on the basis of plate thickness. Temperatures on the order of 800 C are too high for use in straightening the quenched and tempered steels,(17) since this is well into the austenitizing range for such base metals. Guzevich and Okara, et al., (18) have discussed the effect of cold straightening procedures on the properties of low-carbon steel. Such straightening methods had little effect on the tensile properties of the steel; ductility and impact strength were decreased slightly.

Additional information on flame straightening techniques can be found in the <u>Steel Ship Construction Hanbook</u>, prepared by the Society of Naval Architects of Japan, (19) and in an article by Stitt on distortion control.(20)

Limited research has been undertaken to study the effects of flame straightening on the properties of base metals. In 1952 Harrison conducted studies on the principles of flame straightening.(21) In the course of this investigation, mild steel bars (1/4-inch-thick by 2-inches wide by 20-inches long) were bent and straightened; the temperature of the bar stock did not exceed 1300 F during the straightening operation. There was little significant difference in the mechanical properties of these specimens insofar as their tensile strength, impact strength, or hardness was concerned. Further studies of flame straightening as applied to the cambering of steel beams were reported by Crooker and Harrison in 1965.(22) The authors concluded that flame cambering reduced the bending strength of the beams because of unfavorable residual stresses, unfavorable cold work effects, and lateral distortion. The loss in strength could be decreased somewhat by the type of heating pattern used during cambering. These conclusions caused considerable controversy and prompted some discussion of the original article.(23) Apparently, the discussion centered around the method of testing the cambered beams and the definition of failure. For structural purposes, flame cambering had little effect on the design allowables.

Analytical studies of flame straightening phenomena have also been conducted by (1) Wanatabe and Satoh (24) - reduction of distortion by spot heating, (2) Masubuchi (25) and Kihara (26) - analysis of residual stress produced by spot heating, and (3) Maeda and Yada (27,28) - shrinkage distortion produced by single-and multiple-spot heating. Material degradation, per se, was not considered in these investigations.

Heating patterns for flame straightening have been discussed in many of the articles reviewed in this section. The patterns used in the shipbuilding industry are usually variations of the spot or linear heating techniques shown in Figure 6. In spot heating a number of discrete spots (about 3/4 to 1-1/2-inches in diameter) are heated one after another and then cooled; the spots are arranged according to the shape of the area being straightened. Straightening can also be accomplished by heating and cooling along several lines; linear heating can be done from either side of the panel being straightened. Heat can be applied in straight or curved lines; continuous or interrupted heating can be used. In a variation of linear heating (Figure 6c), heating and cooling is done along the back side of a stiffened panel. The relative merits of various heating patterns are subject to debate; each shipyard has preferred heating patterns.



a. Spot Heating Panel

b. Line Heating Panel

c. Line Heating Back of Welds

Fig. 6. Heating Patterns for Flame Straightening

In summary, numerous studies have been conducted on the use of flame straightening techniques to correct or reduce distortion in welded structures; on occasion, the same procedures have been used to produce a controlled amount of distortion in a structural member (a curved beam, for example) to meet design criteria. The practical nature of this process is emphasized by the large number of "how to" articles on flame straightening as opposed to the few theoretical articles on this subject. Even fewer studies have been concerned with the possible degradation of material properties as the result of flame straightening.

Possible Material Degradation as the Result of Flame Straightening

An analysis of flame-straightening procedures indicates that the following parameters are most likely to affect the metallurgical and mechanical properties of the base metals used in ship fabrication:

(1) Maximum straightening temperature
(2) Temperature gradient in the base metal
(3) Heating cycle-time at maximum temperature and cooling rate
(4) Amount and rate of mechanical straining
(5) Number of cycles of heating and straining.

In addition to their possible effects on the transformation characteristics and microstructure of the base metals, these parameters can act to decrease the tensile and impact strength of the base metals as well as influencing the ductile-to-brittle transition temperature. Microcracking can occur as the result of the flame-straightening process and the fatigue life of the base metal can be shortened.* The flame-straightening parameters can act singly or in combination with one another to influence the base metal properties.

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* Fatigue life, as affected by flame straightening, is not to be studied during the current program.

Extensive research on the properties of steels as affected by temperature and strain has been conducted, and there is a vast background of technical literature on these and related subjects. Much of this research has been directed toward determining the behavior of specific steels under real or simulated service conditions. Other pertinent studies have been concerned with the metallurgical and physical properties of weldments made with such steels. Some of these studies have been conducted as part of an overall program to determine the weldability of a specific steel; others have been prompted by difficulties in obtaining the required joint properties in service. For the most part this research has little direct association with the problem at hand; however, some of the information relating material properties to thermal and straining cycles may be applicable to the flame-straightening process and its effect on base metal properties.

This is a limited state-of-the art review of the pertinent literature published during the past 10 to 15 years. It has sometimes been necessary to be selective in citing articles to illustrate a particular point in the discussion, because of the large amount of available information.

Effect of Thermal Cycles During Flame Straightening

It is difficult to pinpoint the temperature used for flame straightening steel structures, because it is frequently specified as the temperature at which the steel has a "dull red" glow. This is an indefinite temperature when determination depends on the operator's ability to discern perceptible changes in color as well as the effect of the surrounding environment. Based on the literature, it is assumed that most flame-straightening operations are conducted at temperatures in the range of 1100-1200 F; excursions 100-300 F wide on either side of this temperature range are quite likely to occur. The cooling rate after flame straightening is also an indefinite parameter. In some cases the heated area is allowed to cool at a rate determined by the radiation characteristics of the base metal, by convection due to air currents, and by the transfer of heat into cooler areas of plate or structure. In other cases the heated area is cooled with a water spray or an air blast to produce a high rate of cooling.

The low-alloy steels with yield strengths ranging from about 45,000 to 75,000 psi are used in the as-rolled or normalized condition; many of the steels used in ship fabrication are included in this category. These steels can be heated to conventional flame-straightening temperatures (~1100-1200 F) without significantly affecting their mechanical properties. At higher straightening temperatures a few microcracks may be observed in the heated area, and some incipient melting may occur. Changes in the microstructure of the base metal can occur due to the effect of the cooling rate on the transformation characteristics of these steels. In 1961, Canonico, et al., reported on research to investigate the effects of accelerated cooling on the properties of steels used in pressure vessels.(29) ABS-B and ABS-C steel plates were water-quenched from a temperature of 1650 F, and the properties of these specimens were determined and compared to the properties obtained with normalized steel plates. Spray-quenching increased the strength and notch ductility of both steels. To determine the effect of thermal straightening on the notch toughness of these steels, articles concerned with the notch toughness at various areas in the weld zone should be consulted. Areas in or just beyond the heat-affected zone of mild steel weldments experience temperatures of the magnitude used in flame straightening. Among such studies are those conducted by Nippes,(30) Masubuchi, et al,(31) Grossman and McGregor,(32) and Stout and Doty.(33) For example, during an investigation on welding 1/2-inch-thick mild steel (0.19C-0.43Mn-0.019Si-0.025P-0.022S). Kihara, et al., observed an increase in the Charpy V-notch 15 ft-lb transition areas in areas just beyond the heat-affected zone; these areas of the steel plate experienced temperatures of 750-930 F. Nippes and Savage studied the variation in notch toughness in specimens that were heated and cooled to duplicate several of the heat-affected structures in a 1/2-inch-thick butt weld in an aluminum-killed steel.(35) Low impact properties were noted in specimens that represented a region well beyound the heat-affected zone. It, during flame straightening, heat is applied directly to a welded joint, the metallurgical reactions are more complex; however, the effects of the flame-straightening procedure on the mechanical properties of the welded joint should be insignificant also as long as the straightening temperature is not excessive. The joint ductility would probably increase slightly, since the joint would be stress relieved.

Such is not the case with the high-strength, low-alloy steels that have yield strengths in the order of 100,000 psi. These steels are furnished in the quenched-and-tempered condition, and the temperatures and cooling rates involved in flame straightening can have a serious effect on the microstructure and mechanical properties of unwelded and welded plate. These steels acquire their properties by water-quenching from a temperature of about 1600-1750 F and tempering at 1050-1275 F.* Depending on the composition of the steel and the heat treatment, the microstructure consists of (1) ferrite plus tempered bainite or martensite, or (2) tempered bainite and martensite. The composition and mechanical properties of representative high-strength, low-alloy steels are shown in Tables 1 and 2; most of these alloys have been used or are candidates for use in ship construction.(36) The transformation characteristics of two of these alloys (Grades B and F in Table 1) are shown in Figure 7; these curves illustrate the variation in transformation behavior that must be considered in flame straightening a particular high-strength steel. In Figure 7a a considerable period of time elapses before this steel starts to transform in the pearlite transformation range of about 1300-1100 F. This lapse of time insures that transformation to these undesirable high-temperature transformation products will not occur unless the cooling rate is very slow. Because of its lower alloy content, the period of time that elapses before transformation starts in the Grade B steel (Figure 7b) is much shorter than that of the Grade F steel. In the Grade F steel, a moderately long period of time elapses before transformation starts in the ferrite and upper bainite temperature range of about 1100-950 F. As a result, relatively thick plates (up to at least 2 inches thick) can be quenched with little or no transformation in this temperature range. This period of time is shorter for the Grade B steel, and the thickness of plates that can be quenched to produce the desired low-temperature bainitic or martensitic microstructures is 1-1/4 inches or less. The transformation products (soft ferrite, upper bainite, and high-carbon martensite) that are produced in this temperature range have a degrading effect on the notch toughness behavior of the steel even when tempered. The curves indicate that transformation to low-temperature bainitic structures occurs in a relatively short time for both steels, and that transformation to martensite occurs at a relatively high temperature.

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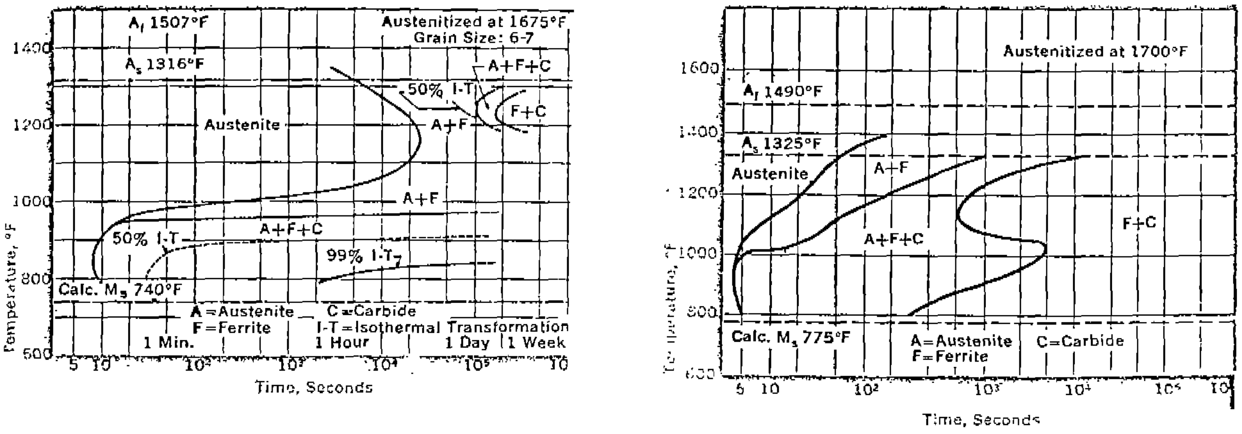
* The temperature from which the steel is quenched and the tempering temperature depend on the composition of the steel and the required strength level.



a. Grade F (Table 1)

b Grade B (Table 1)

Fig. 7. Isothermal Transformation Diagrams for Two High-Strength, Low-Alloy Steels

Problems caused by the effects of temperature alone on base metal properties can be encountered when the high-strength, low-alloy steels are flame straightened.* The extent and severity of these problems can be anticipated by the care that must be exercised in welding these materials, particularly with respect to the permissible heat input during welding. Extensive research on the weldability of the quenched-and-tempered low-alloy steels and on related subject areas has been conducted by Government and industry, and comprehensive procedures for welding such steels have been established. A few of the many articles on this subject are included in the reference list. (37-48) In general, the weldability of the quenched-and-tempered low-alloy steels is excellent when the following welding processes are used: shielded metal-arc, gas-shielded metal-arc, and submerged arc. The weld-cooling rates for these processes are so rapid that the mechanical properties of the heat-affected zone of the steels approach those of the base metals in the quenched condition. Reheat treatment is not required. Welds made with high-heat input processes, such as electroslag welding, must be heat treated after welding. Aside from the need to design the joint properly and use properly conditioned low-hydrogen electrodes (assuming that welding is being done by the shielded metal-arc process), the most important considerations in welding the high-strength, low-alloy steels is to select the proper preheat temperature and limit the heat input during welding to recommended levels. Suggested preheat temperatures for several of the steels listed in Table 1 are shown in Table 3; maximum heat inputs for Grades B and F steels are shown in Tables 4 and 5. The maximum heat inputs have been selected to maintain adequate notch-toughness in the heat-affected zone; the strength properties of the heat-affected zone are not as sensitive to heat input as the notch-toughness, so higher heat inputs could be used if notch toughness were not

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* These problems are accentuated when the combined effects of temperature and strain on base metal properties are encountered. This subject is discussed in the next section of this report.

Table 1. Chemical Composition of Several Heat-Treated Steels.

Table 1. —Chemical composition of several heat-treated steels

Type		C	Mn	P[1]	S[1]	Si	Cu	Ni	Cr	Mo	V	B	Ti
No. 1	Range	0.20 max	0.70–1.35	0.04 max	0.05 max	0.15–0.50	Present in small quantities						
	Typical	0.17	1.25	0.01	0.02	0.35	0.25	0.15	0.12	0.04	...	...	...
No. 2	Range	0.20 max	1.50 max	0.04 max	0.05 max	0.30–0.60	0.20–0.40	... ...	... ...	... ...	... ...	... ...	... ...
	Typical	0.17	1.35	0.01	0.02	0.40	0.30	...	...	...	...	...	...
HY-80	Range	0.18 max	0.10–0.40	0.025[2] max	0.025[2] max	0.15–0.35	0.25 max	2.00–3.25	1.00–1.80	0.20–0.60	0.03 max	...	0.02 max
	Typical	0.16	0.28	0.015	0.016	0.23	0.05	2.97	1.68	0.45	0.005	...	0.005
A517 Grade A		0.15–0.21	0.80–1.10	0.035	0.040	0.40–0.80	...	...	0.50–0.80	0.18–0.28	...	0.025 max	...
A517 Grade B		0.12–0.21	0.70–1.00	0.035	0.040	0.20–0.35	...	...	0.40–0.65	0.15–0.25	0.03–0.08	0.0005–0.005	0.01–0.03
A517 Grade C		0.10–0.20	1.10–1.50	0.035	0.040	0.15–0.30	...	...	...	0.20–0.30	...	0.001–0.005	...
A517 Grade D		0.13–0.20	0.40–0.70	0.035	0.040	0.20–0.35	0.20–0.40	...	0.35–1.20	0.15–0.25	[3]	0.015–0.005	0.04 0.10
A517 Grade E		0.12–0.20	0.40–0.70	0.035	0.040	0.20–0.35	0.00–0.40	...	1.40–2.00	0.40–0.60	[3]	0.0015–0.005	0.04–0.10
A517 Grade F		0.10–0.20	0.60–1.00	0.035	0.040	0.15–0.35	0.15–0.50	0.70–1.00	0.40–0.65	0.40–0.60	0.03–0.08	0.002–0.005	...
Grade G		0.15–0.21	0.80–1.10	0.036	0.040	0.50–0.90	...	...	0.50–0.90	0.40–0.60	...	0.0026 max	...

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[1] For firebox quality phosphorus is 0.035 max and sulfur 0.040 max.

[2] The phosphorus and *sulfur together should not* exceed 0.045.

[3] May be substituted for part or all titanium content on a one-to one-basis.

Table 2. Properties of Longitudinal Tensile and Charpy V-Notch Impact in Heat-Treated St

Table 2.—Properties of longitudinal tensile and Charpy V-notch impact in heat-treated steels

Type (see Table 63.14)	Thickness range (in.)	Yield Point or Strength (Range or min) psi x 10³	Tensile Strength (Range or min) psi x 10³	Minimum Elongation in 2 in. percent (min)	Reduction in Area, % (min)	Energy Abso V-notch Impact
						Longitudina
NO. 1	To 1¼, incl.	60	80–100	23[1]		15@-75°F
	Over 1¼ to 2, incl.	56	75–95	23[1]		15@-75°F
NO. 2	To ¾, incl.	80	100	18		
	Over ¾ to 1½, incl.	70	90	20		
HY-80	Less than ⅝	80–100		19		60@-120°F (½ inch and
	⅝ to 2, incl.	80–95		20	55	60@-120°F
A517	Over 2	80–95		20	55	30@-120°F
GRADE F	3/16 to 2½, incl.	100	115–135	18[2]	50[3]	20@-50°F[4]
	Over 2½ to 4, incl.	90	105–135	17	50	30@-0°F
A517	Over 4 to 6, incl.	90	105–135	16	45	
GRADE B	3/16 to ¾, incl.	100	115–135	18[2]	40	15@-50°F
	¾ to 1¼, incl.	100	115–135	18	50	

[1] For firebox quality elongation in 2 inches is 24%.

[2] Elongation for plates under ¼ inch is 15%.

[3] Reduction in area 40% (min) for plates to ¾ inch, incl.

[4] To 2½ inch incl.

of primary importance. In shielded metal-arc welding, the stringer-bead technique should be used without appreciable transverse oscillation to minimize the heat input; deposition techniques that prolong heating should be avoided. Welded joints made with high-strength, low-alloy steels usually do not require stress relieving unless dimensional stability must be maintained or stress corrosion may be involved. Notch-toughness tests have shown that toughness in the weld metal and heat-affected zone may be impaired by postweld heat treatment in the 110-1200 F temperature range, especially if the steel is cooled slowly as in the case of stress relieving. Intergranular cracking in the grain-coarsened region in the heat-affected zone may occur also.

What, then, are the effects of temperature on the properties of high-strength, low-alloy steels when they are flame straightened? If an unwelded plate section is flame straightened at temperatures below 1100-1200 F, it is not expected that the base metal properties will be seriously affected, although there probably will be some loss in ductility and notch toughness; this is quite similar to a retempering operation. The degradation of base metal properties becomes more serious when the distorted plate section contains a welded joint. If the temperature in the joint area reaches 950-1200 F during the straightening operation, the notch-toughness properties of the weld metal and heat-affected zone are adversely affected if the plate is cooled slowly. Doty noted a considerable increase in the Charpy V-notch transition temperature when ‵T-1′ welded joints were stress relieved at 1200 F.(49) These effects should be less pronounced if the plate is quenched with a water spray after straightening. Also, as mentioned above, intergranular cracking in the heat-affected zone has been observed when welded high-strength steel joints were heated to these temperatures. Such cracking occurs by stress rupture in the early stages of the stress-relief treatment before the high residual tensile stress from welding has been significantly reduced.(39-50)

The consequences are far more serious if either a welded or unwelded plate section is heated above the lower critical temperature of the base metal during the flame-straightening operation. For example, Burbank flame-heated unwelded sections of ‵HTS′ steel plate, 3/8 inch thick, to temperatures between 975 and 1490 and water-quenched them.(51) These specimens showed a decrease in Charpy V-notch impact strength when they were tested immediately after straightening; a further decrease was noted in specimens that were tested 6 months later. A similar behavior was observed when 5/8-inch-thick plate was heated and quenched. Guided bend tests conducted with these materials were generally unsatisfactory. Burbank noted an improvement in base metal properties when the plate was held at a temperature of 1100 F for one-half hour after straightening, followed by slow cooling to 500 F and air cooling to room temperature. Further evidence of the problems that can be encountered during flame straightening is contained in a case history cited by Doty in a comprehensive article on the welding of quenched-and-tempered steels.(44) A penstock fabricator found cracks and water leaks when large Y-branch pipes were pressure tested. The cracks were located in a transition section of ‵T-1′ steel that was hot-formed to produce a flare fitting. Before hot-forming, the transition section was heated to about 2200 F. After forming, the fitting was cooled. Then, it was reheated with gas burners, water-quenched, and retempered. Examination showed that the reheat-treated region contained material that had been heated to a temperature as high as 2200 F for about 10 minutes before cooling; during tempering, some areas of the transition section had been heated to 1250 F while others had been heated only to 1050 F. The recommended temperature ranges for austenitizing and tempering ‵T-1′ steel are 1650-1750 F and 1100-1275 F, respectively. Because of this irregular heat treatment, the material in the locally reheat-treated region had an undesirable microstructure and failed by stress rupture during a subsequent furnace stress-relieving operation.

It is not likely that flame straightening will be conducted at temperatures above 2000 F; however, the temperature in a localized area of a plate being straightened may exceed the lower critical temperature of the steel and even approach or exceed the upper critical temperature. In either case, the mill heat treatment is upset. In the case of "T-1" steel, if complete or partial austenitization occurs, some undesired transformation may occur in the 1300-1100 F temperature upon slow cooling. Further transformation may occur in the ferrite and upper bainite temperature region (1100-950 F) to produce an undesirable microstructure consisting of soft ferrite, upper banite with retained austenite, high-carbon martensite, or high-carbon bainite. This microstructure is very undesirable from the notch-toughness standpoint. If the plate section being flame straightened contains a welded joint, the situation is even more complex and serious because notch toughness in the heat-affected zone is highly dependent on its microstructure.

Thus, flame straightening of high-strength, low-alloy steel structures must be approached with caution and a thorough knowledge of the metallurgical consequences that can occur because of improper straightening procedures.

Effects of Thermal Cycles and Plastic Strain During Flame Straightening

Thus far, only the effects of temperature on base metal properties during flame straightening have been considered. However, strain is always present during these operations, since the structure is plastically deformed through thermal or mechanical processes to achieve the required degree of straightness.

It has been recognized that plastic straining at room temperature reduces the available plastic-deformation capacity by an amount at least equal to the prestraining. Often, however, much less ductility is retained than would be estimated from the prestraining. An important factor which causes the drastic reduction of ductility is aging, a condition to which plastically strained metal is quite prone. Another important factor is the change of shape of the discontinuities during prestraining; when defects are present in the material before straining, prestraining will modify the shape of these defects. Straining of a flawed material in uniaxial tension blunts the flaw and in many circumstances has a beneficial effect. But detrimental effects result when prestraining sharpens the defect root. This may occur when prestraining is obtained by transverse straining in tension and final testing is undertaken with longitudinal tension. Severest damage results when prestraining in compression in the same direction precedes final tensile testing.

Many research programs have been conducted to study the effects of plastic strain and thermal cycles, which occur during welding and other operations, on material properties. However, only limited study has been made specifically on material degradation due to distortion-straightening treatments. Thermal and plastic changes that take place during the straightening treatments are different from those that take place during other treatments. Therefore, the nature and extent of material degradation caused by straightening treatments may be radically different from that caused by other treatments.

Table 3. --Comparison Chart of Suggested Preheat Temperatures when Arc Welding Several Different Steels

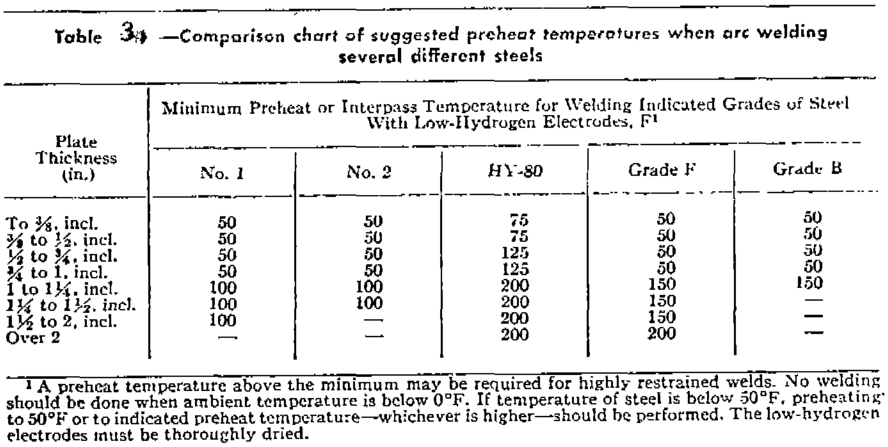


Table 3 —Comparison chart of suggested preheat temperatures when arc welding several different steels

Plate Thickness (in.)	Minimum Preheat or Interpass Temperature for Welding Indicated Grades of Steel With Low-Hydrogen Electrodes, F[1]				
	No. 1	No. 2	*HY-80*	Grade F	Grade B
To ⅜, incl.	50	50	75	50	50
⅜ to ½, incl.	50	50	75	50	50
½ to ¾, incl.	50	50	125	50	50
¾ to 1, incl.	50	50	125	50	50
1 to 1¼, incl.	100	100	200	150	150
1¼ to 1½, incl.	100	100	200	150	—
1½ to 2, incl.	100	—	200	150	—
Over 2	—	—	200	200	—

[1] A preheat temperature above the minimum may be required for highly restrained welds. No welding should be done when ambient temperature is below 0°F. If temperature of steel is below 50°F, preheating to 50°F or to indicated preheat temperature—whichever is higher—should be performed. The low-hydrogen electrodes must be thoroughly dried.

Table 4. --Maximum Welding Heat Input in Joules/inch for Butt Joints in Grade F Steel

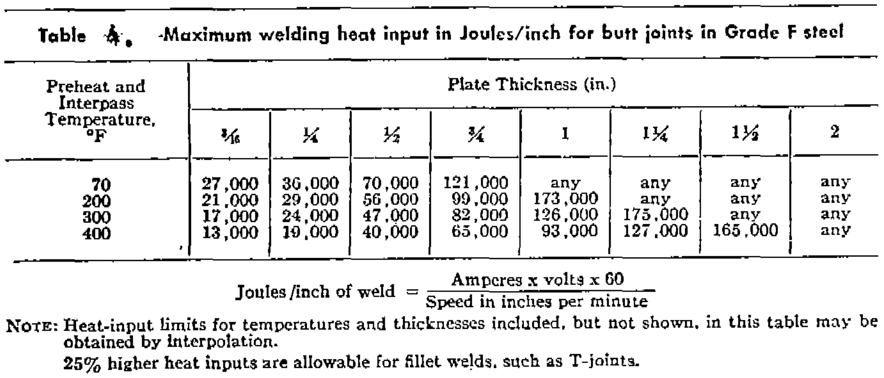


Table 4. -Maximum welding heat input in Joules/inch for butt joints in Grade F steel

Preheat and Interpass Temperature, °F	Plate Thickness (in.)							
	3/16	¼	½	¾	1	1¼	1½	2
70	27,000	36,000	70,000	121,000	any	any	any	any
200	21,000	29,000	56,000	99,000	173,000	any	any	any
300	17,000	24,000	47,000	82,000	126,000	175,000	any	any
400	13,000	19,000	40,000	65,000	93,000	127,000	165,000	any

$$\text{Joules/inch of weld} = \frac{\text{Amperes x volts x 60}}{\text{Speed in inches per minute}}$$

NOTE: Heat-input limits for temperatures and thicknesses included, but not shown, in this table may be obtained by interpolation.

25% higher heat inputs are allowable for fillet welds, such as T-joints.

Table 5. --Maximum Welding Heat Input in Joules/inch for Butt Joints in Grade B Steel

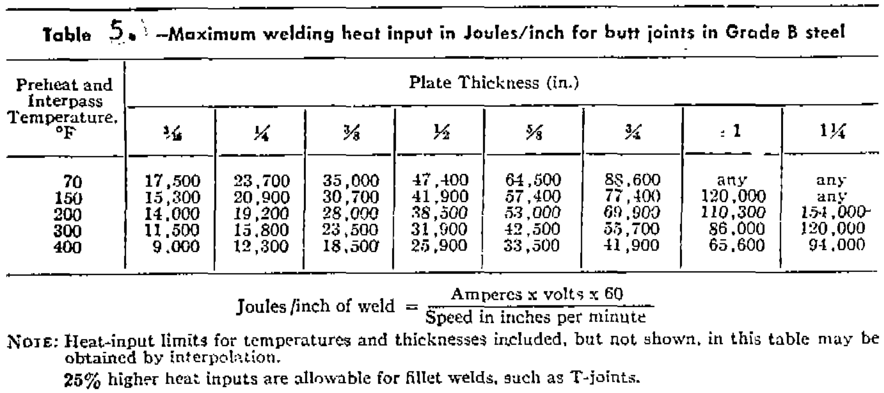


Table 5. —Maximum welding heat input in Joules/inch for butt joints in Grade B steel

Preheat and Interpass Temperature, °F	Plate Thickness (in.)							
	3/16	¼	⅜	½	⅝	¾	1	1¼
70	17,500	23,700	35,000	47,400	64,500	88,600	any	any
150	15,300	20,900	30,700	41,900	57,400	77,400	120,000	any
200	14,000	19,200	28,000	38,500	53,000	69,900	110,300	154,000
300	11,500	15,800	23,500	31,900	42,500	55,700	86,000	120,000
400	9,000	12,300	18,500	25,900	33,500	41,900	65,600	94,000

$$\text{Joules/inch of weld} = \frac{\text{Amperes x volts x 60}}{\text{Speed in inches per minute}}$$

NOTE: Heat-input limits for temperatures and thicknesses included, but not shown, in this table may be obtained by interpolation.

25% higher heat inputs are allowable for fillet welds, such as T-joints.

Thus there is a need for the proposed study, which is directed specifically toward the effects of straightening treatments. Nevertheless, some of the information concerning material degradations which occur in other treatments should be useful in the proposed study.

A recent book, prepared by Hall, Kihara, Soete, and Wells, provides a good background on the effects of plastic strain and temperature on the properties of steels, especially ordinary carbon steels.(44) Work with the high-strength, low-alloy steels is more limited.

Tensile Straining at Room Temperature. Effects of straining by tension at room temperature on material properties have been studied by several investigators including Mylonas.(53, 54) Mylonas prepared flat specimens of low-carbon steel, 10 inches wide, containing machined notches on their sides. The notched specimens had been subjected to various amounts of prestrain at room temperature, and final tensile tests at low temperatures (between -12 and -3 F). The plates that were prestrained in tension transversely to the direction of testing failed at average stresses below virgin yield, the lowest value being 70 percent of virgin yield. In contrast, all the plates that were prestrained longitudinally failed generally at or above the virgin yield, but below the raised yield point.

These tests illustrate the important role of the direction of prestraining and confirm generally that prestraining that increases the shallowness of defects increases the embrittlement, while prestraining that provokes blunting of the defects leads to a lesser degree of embrittlement.

Compressive-Straining at Room Temperature. The effect of prestraining by compression at room temperature also was investigated by Mylonas.(53,55) Notched specimens were subjected to various amounts of prestrain in compression. After prestraining, which was done at room temperature, the specimens were kept at -25 F up to the time of testing, in order to minimize aging effects. Tensile tests were made at temperatures in the range of about -12 to 0 F. All fractures had a brittle appearance. Test results were interpreted as a function of the maximum applied stress in percentage of virgin yield. Many of the specimens broke before full yielding occurred. One specimen failed at an average stress of 12 percent of virgin yield, and cracking was observed at average stresses as low as 9 percent of virgin yield.

Satoh and Mylonas also conducted studies to determine the effect of surface finish on the compressive prestraining needed to exhaust the tensile ductility of the steel.(56) Bars of ABS-C steel with as-rolled and machined surfaces were prestrained by bending; the effects of surface finish and amount of prestrain were determined by a reversed bend test prepared by Ludley and Drucker.(57) Bars with machined surfaces had a slightly higher exhaustion limit than those with as-rolled surfaces; the difference is somewhat more pronounced for bars tested at -16 F than for those tested at room temperature.

In more recent work, Mylonas, Kobayashi, and Armenakas have been concerned with the effect of strong constraint on the ductility of prestrained

ABS-B and E-steel bars.(58) The desired amount of constraint was obtained by machining a deep circumferential groove in prestrained and aged (330 F for 2 hours) cylindrical bar specimens. The specimens were tested in tension at -16 F and room temperature. The experimental results indicated a severe reduction in ductility for bars that were notched; the embrittling prestrain decreased from about 0.75 for smooth bars (ABS-B steel) to 0.05 for notched bars. In 1968, Kabayashi and Mylonas discussed the effect of small discontinuities (represented by small holes drilled in the bar stock before prestraining by compression) on the prestrain required to produce brittleness.(59) The existence of these discontinuities reduced the amount of compressive prestrain causing brittleness to (1) one-third or one-fourth the amount needed in solid bars of E-steel, and (2) two-thirds to one-fourth the amount needed in solid bars of ABS-B steel.

The data on high-strength, low-alloy steels are more limited than those available for low- and medium-strength steels. In evaluating the reversed bend test, Ludley and Drucker included data on `T-1´ steel.(57) Also, Doty studied the effect of compressive prestraint (obtained by cold reduction of plate stock) on the ductility-transition temperature of `T-1´ steel.(49) Prestrainiing produced an increase of about 33 F in the transition temprature; this temperature was increased by 63 F when the prestrained specimen was aged at 550 F for one hour. Stress relieving the specimens after prestraining produced a slight decrease in the transition temperature. In 1967, Armenakas and Mylonas discussed the effect of compressive prestraining (produced by bending bar stock to obtain the desired amount of prestraining) on the ductility properties of 18 percent nickel maraging steel and two titanium alloys, Ti-6Al-4V and Ti-13V-11Cr-3Al.(60) The ductility of the maraging steel dropped sharply at a prestrain of 0.50; the ductility of the titanium alloys decreased more gradually with increasing prestrain.

Tensile Prestraining at High Temperature. Various investigators including Terazawa, et al.(61) and Soete, et al.(62) reported tests where prestraining was accomplished by tension at high temperatures and final fracture testing was done at room or low temperature.

Figure 8 shows results obtained by Terazawa, et al. on killed steel 1 inch thick. Cylindrical specimens were prestrained by tension at different temperatures up to 1110 F (600 C). Strains up to 70 percent were applied to the specimens. The final tests were performed at room temperature 1 or 2 days after prestraining. The test results, presented in Figure 8, indicate that for a flawless material tested at room temperature, the total ductility is independent of the amount of prestraining at room temperature and equal to the ultimate strain obtained in a single tension test. However, when prestraining is done at higher temperature there is a substantial loss of ductility. For the steel involved here, 390 F (200 C) and 930 F (500 C) appeared to be the most damaging temperatures. The loss of ductility at the higher temperatures appears important for prestraining of 10 percent or more. It is important to observe that the fracture stress was practically independent of the amount of prestraining and the temperature of prestraining.

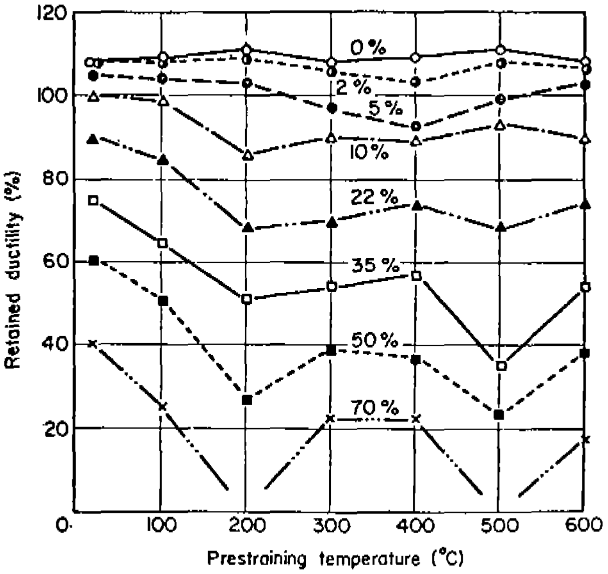


Fig. 8. Tensile Prestrain Tests for Cylindrical Specimens(61)

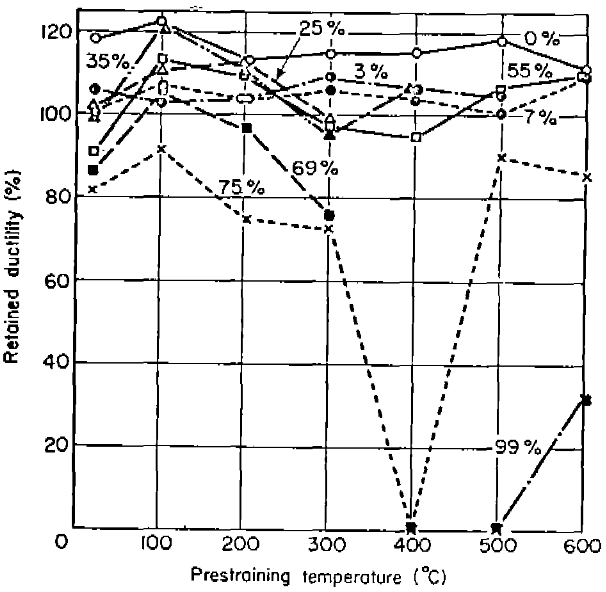


Fig. 9. Compressive Prestrain Results for Cylindrical Specimens(61)

Compressive Prestraining at High Temperature. The tests by Mylonas, previously mentioned, illustrated the danger of prestraining notched specimens at room temperature. It is likely that if this prestraining is done at some critical temperature even more catastrophic results may be expected. Studies were made of the effects of temperature and plastic straining by compression on unnotched specimens by several investigators.

For example, Korber, et al.(63) conducted fracture tests at room temperature of cylindrical specimens that had been prestrained by compression at different temperatures. The specimens were made from a Basic Bessemer steel, an open-hearth steel, and a cast steel. Undamaged (unprestrained) specimens contracted about 70 percent in laminated steel and about 60 percent in cast steel, while prestrained specimens contracted less than 5 percent. The most dangerous temperaure was around 480 F.

Terazawa, et al., conducted similar tests with a mild steel.(61) The specimens were prestrained at temperatures of 100, 300, 400, 500, and 600; the amount of prestraining ranged from 0.3 to 75 percent. The results of this study are summarized in Figure 9. Serious embrittlement occurred when the steel was prestrained about 70 percent at temperatures between 200 and 500 C.

Plastic Straining by Bending. Tests made by Korber, et al. have shown that for each temperature of prestraining there appears to be a critical strain above which steels behave brittlely in a subsequent tensile test. This critical strain has been called the exhaustion limit by Mylonas. This exhaustion limit depends on both the temperature at which the prestraining has been done and the temperature of the final tensile tests.

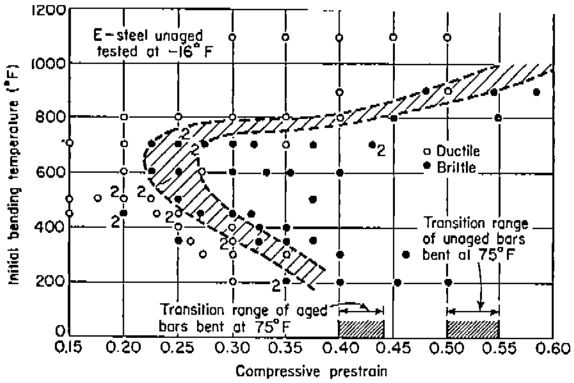


Fig. 10. Reversed-Bend Tests of Unaged Bars of E Steel Prestrained at Various Temperatures (64)

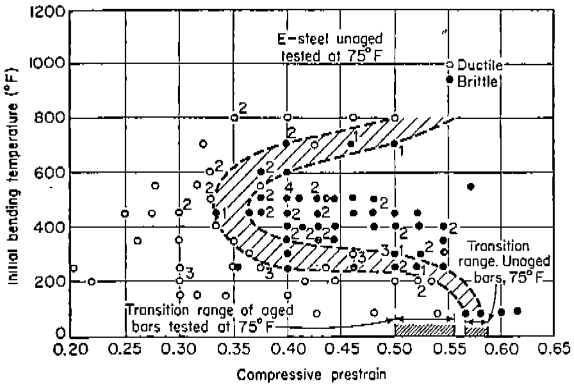


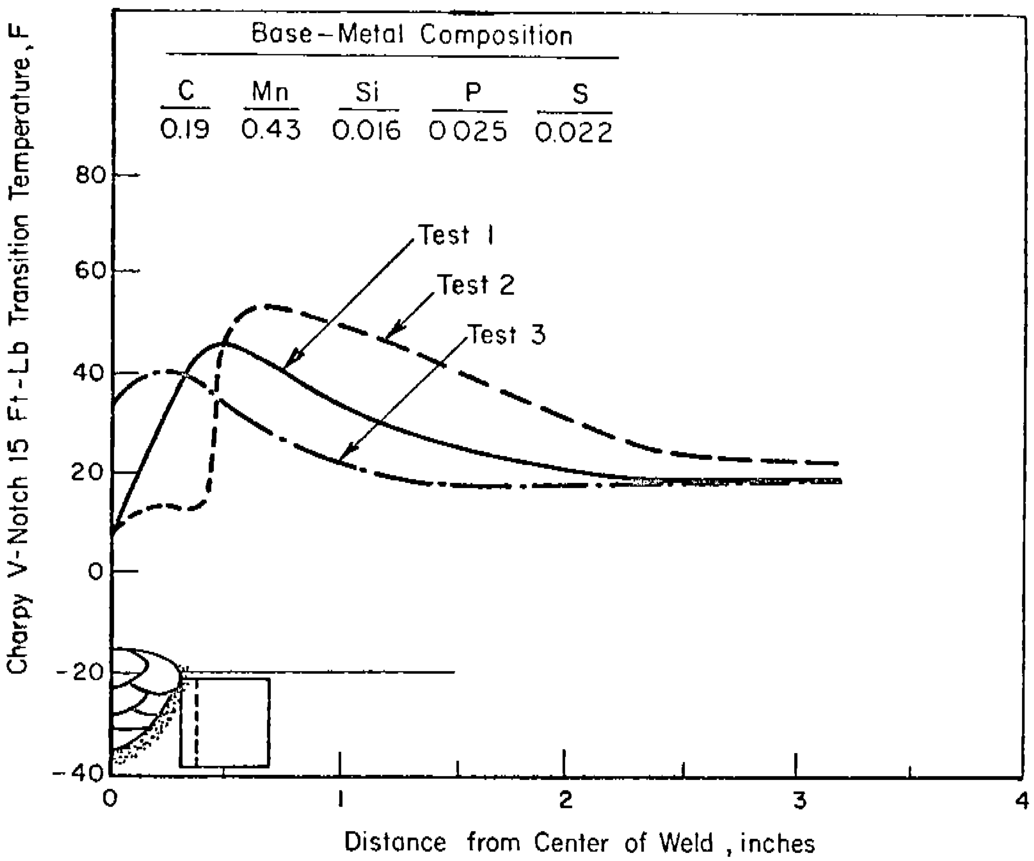
Fig. 11. Reversed-Bend Tests of Unaged Bars of E Steel Prestrained at Various Temperatures (64)

The reversed-bend test prepared by Ludley and Drucker to simulate plastic straining by compression has already been mentioned. In this procedure, a bar specimen is prestrained by bending to produce the desired amount of compressive prestrain on the intrados (the concave section of the curved bar).(57) Then, reversed bending is done in a tensile machine to produce tension on the intrados. In 1962, Rockey, Ludley, and Mylonas determined the effect of various amounts of compressive prestrain on the ductility of the following steels: E-steel, A7, ABS-C, T-1, and HY-80.(64) The results for tests conducted with E-steel are shown in Figures 10 and 11. Also shown in these figures are the transition ranges of aged and unaged bars of E-steel.

The fracture toughness and fracture-toughness transition temperature of two mild steels was also determined with another bending test by Dvorak.(65) In this test, machined bars were prestrained in compression by four-point loading. Three-point loading was used to conduct the reverse-bend tests.

Impact Tests on Plastically Strained Material. Many programs have been conducted to study the effect of plastic straining at different temperatures on the impact value of embrittled steel. The results are generally interpreted as a function of the increase in the conventional transition temperature. For example, Terazawa, et al., conducted Charpy impact tests of carbon steel that had been prestrained to various levels (up to 70 percent) at different temperatures (up to 1100 F).(66) Transition temperatures increased considerably when the steel was subjected to plastic straining of about 35 percent at a temperature between 400 and 550 F.

Specimens Prepared from Weldments. As described in a ship structure committee report prepared by Masubuchi, et al.(67), many investigators have studied notch toughness at various locations of a welded joint. In most cases, Charpy impact specimens were used; however, other specimens, including notched-bar tensile or bending specimens, also have been used. Figure 12 shows distributions of the Charpy V-notch 15 ft-lb transition temperatures in 1/2-inch-thick carbon-steel welds made by shielded metal-arc and submerged processes.(60) Transition temperatures were high in areas 0.4 to 0.6 inch from the weld center, somewhat outside the heat-affected zone. The maximum temperature of the embrittled zone attained during welding was 750 to 930 F.



Welding Conditions

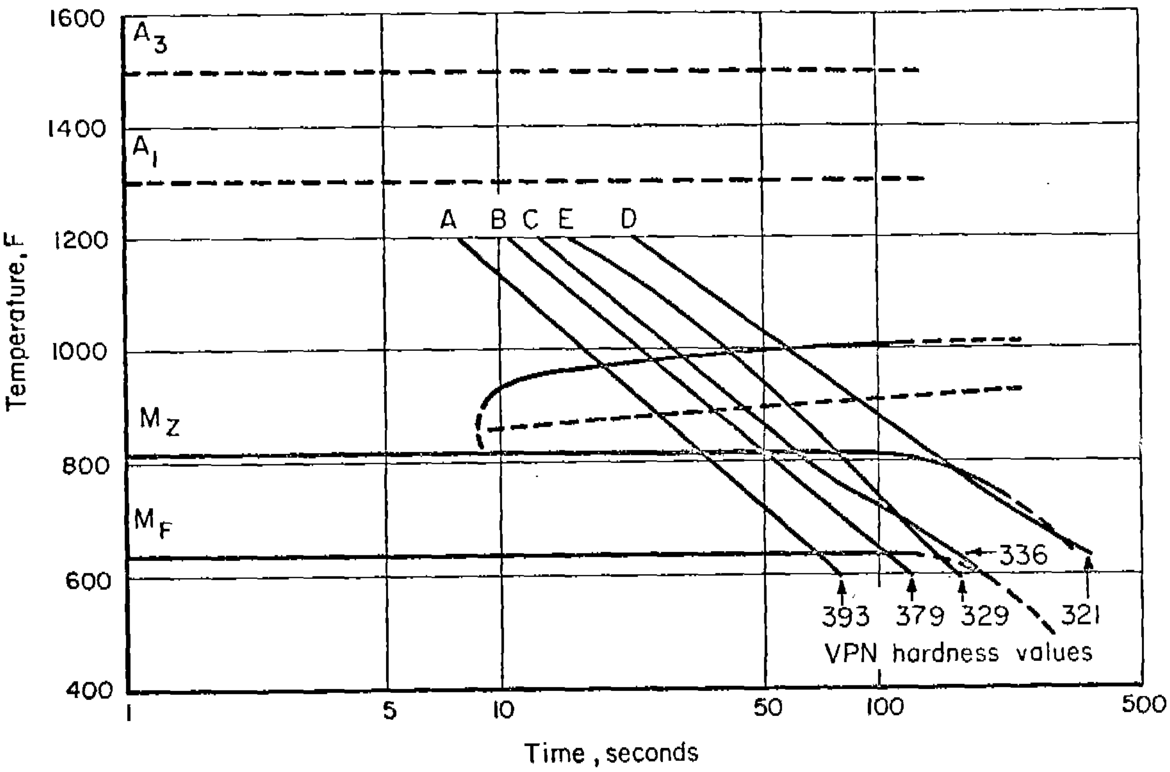
Test	Welding Method	Shape of Groove	Welding Current, amperes	Welding Speed, in./min
1	Shielded metal-arc	60°V, 0.35" deep	160	8.0(a)
2	Submerged-arc	60°V, 0.16" deep	600	11.5
3	Submerged-arc	60°V, 0.12" deep	500	34.0

(a) For each pass.

Fig. 12. Distribution of Charpy V-Notch 15-FT-LB Transition Temperature in Groove Welds in ½-inch-thick Mild-Steel Plates Made with Shielded Metal-Arc and Submerged-Arc Processes (68)

The above investigation and many other investigations have shown that notch toughness is the lowest in areas well outside the zone usually considered the heat-affected zone. However, this embrittled zone does not appear to be important in the brittle fracture of welded structures. Brittle fractures that occurred in ships and other structures frequently initiated from the heat-affected zone and weld defects. However, no brittle fracture has been reported that initiated from the embrittled zone near the weld. Nor do brittle fractures propagate through the embrittled zone.

Tests on Specimens Subjected to Simulated Thermal Cycles. Many investigators, including Nippes and Savage(30,35,69,70) conducted tests on specimens subjected to simulated thermal cycles. Most of the tests conducted so far have investigated properties of the heat-affected zone of the weld.



Results Obtained with Synthetic Thermal-Cycle Specimens

Thermal Cycle	Energy Input, j/in.	Initial Plate Temp, F	Peak Temp, F	Hardness, VPN	Weld Cooling Rate at 900 F, F/sec	Charpy V-Notch Transition Temp, F 10 Ft-Lb	Fracture Appearance
A	47,000	72	2400	393	12.8	-138	+5
B	47,000	200	2400	379	8.7	-100	+25
C	47,000	300	2400	336	6.3	-47	+68
D	47,000	500	2400	321	2.5	+26	+152
E	75,600	72	2400	329	4.5	-16	+71

Fig. 13. Weld Thermal Cycles Indicated on Continuous-Cooling Transformation Diagram of Quenched and Tempered High-Strength Steel (69)

The synthetic-specimen technique has been quite useful for studying the notch toughness of the heat-affected zone in high-strength steels which undergo complex transformation during welding.

The effect of the cooling rate on microstructure and notch toughness can be investigated systematically with the combined use of the synthetic-specimen technique and the continuous-cooling transformation (CCT) diagram. Figure 13 shows the CCT-diagram of a quenched-and-tempered steel (100,000 psi yield strength). Also shown here are weld thermal cycles as follows:

(1) Thermal cycles, A, B, C, and D, which represent cooling curves for the heat-affected zone structures with a 2400 F peak temperature in 1/2-inch-thick butt welds (heat input: 47,000 joules/inch) with various preheating temperatures up to 500 F

(2) Thermal cycle E, which represents a cooling curve of the heat-affected zone in a weld made with a 75,000 joules/inch heat input.

The notch toughness of synthetic specimens that underwent thermal cycles A through E is shown in the note of Figure 13. Notch toughness decreased markedly when the cooling rate was reduced by either increasing initial plate temperature or increasing energy input. The investigators explained that the poor behavior of the slowly cooled heat-affected zone was due to the fact that low-carbon martensite, which has excellent notch toughness, was gradually replaced by a mixture of ferrite and high-carbon martensite or banite. It must be mentioned, however, that the effects of welding thermal cycles on' notch toughness of the heat-affected zone depend greatly upon the composition and microstructure of the material. In the case of hardenable steels containing moderate amounts of carbon, rapid cooling rates generally cause formation of brittle martensite. Similar studies with D6ac steel were also conducted by Nippes and Emmerich.(70)

Discussion

A review of the literature was conducted to determine the effects of flame straightening on the properties of the base metals being straightened. Flame straightening procedures are used extensively in the shipbuilding industry to remove or correct distortion caused by welding and other assembly methods. The techniques of flame straightening are well-established and there is considerable information available on heating equipment, heating patterns, etc. However, there is a lack of substantiated data that directly relate the physical and mechanical properties of the base metals to the flame straightening parameters. With the increasing use of high-strength, low-alloy steels in ship fabrication, there is a need for such information, because the properties of these materials are quite susceptible to degradation by unwise handling.

The parameters that are most likely to affect base metal properties during straightening are temperature, strain, and various combinations of temperature and strain. The results of the literature search are discussed briefly on the basis of these parameters.

(1) Temperature. The temperature to which steel plate is heated for straightening can have a significant bearing on the properties of the base metal. The medium-and high-strength, low-alloy steels are much more sensitive to the effects of temperature than the low-strength steels. So long as prolonged heating of the low-strength steels does not occur in a temperature range where they are

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susceptible to brittleness, it is not expected that flame straightening will affect their temperatures markedly. Such is not the case with the higher-alloyed quenched and tempered steels. If straightening is conducted at temperatures in excess of the lower critical temperature, these steels will partially transform and undesirable microstructures can form as the steel is cooled; heating to these temperatures will also alter the mill heat treatment of these steels. Prolonged heating at lower temperatures can also promote the formation of brittle microstructures.

The literature contains numerous references to the effect of temperature on base metal properties. Isothermal transformation diagrams are mostly used in determining the effects of reheating steels for straightening. Other pertinent data can be obtained from weldability studies, studies of the heat-affected zone in welds, etc.

(2) Strain (and Temperature). Extensive studies have been conducted to determine the effects of strain at various temperatures in the brittle fracture characteristics of many of the low- and medium-strength steels used in shipbuilding; comparable data on high-strength steels are not so readily available because fewer studies with these materials have been undertaken. However, the strains (extending up to about 75 percent) investigated during these programs are generally much higher than those to be encountered in the conventional straightening of plate that has been distorted by welding. Thus, this information is of limited value in the current program. The available data indicate that low strains (less than 5 percent) have little effect on the base metal properties.

The current research program will provide some data on material property degradation as the result of flame straightening and mechanical straightening at elevated temperatures. The straightening of steel plates, pre-bent to produce small strains, will be conducted at temperatures near 1200 F for the most part; a few straightening experiments will be conducted at temperatures above and below this commonly accepted flame-straightening temperature. Steels with yield strength levels of from 50,000 to 100,000 psi are included in this work. These data should be supplemented at a future date with additional information on the behavior of these and other steels used in shipbuilding over a more complete range of temperatures. The experimental program plan for the present research is shown in Table 6. Plate specimens subjected to the various treatments will be evaluated by various mechanical property and metallurgical tests. The primary evaluation method will be based on full section drop-weight tear tests.

Table 6. Schedule for Straightening Studies (Unwelded and Welded Test Specimens)

Code Number	Type of Steel	Plate Thickness, inch	Amount of Distortion, inch	Mechanical Straightening Temperature, F	Thermal Straightening Temperature, F	Number of Test Plates
1	A517	1/2	None	-	-	2
2	Ditto	Ditto	7/16	1300	-	2
3	"	"	Ditto	1000	-	1
4	"	"	"	RT	-	1
5	"	"	9/64	1300	-	1
6	"	"	Ditto	RT	-	1
7	"	"	7/16	-	1300-1400	2
8	"	"	Ditto	-	1100-1200	1
9	A517	3/8	None	-	-	2
10	Ditto	Ditto	1/2	1200	-	1
11	"	"	Ditto	RT	-	1
12	"	"	"	-	1300-1400	1
12a	"	"	"	-	1100-1200	1
13	A517	3/4	None	-	-	2
14	Ditto	Ditto	3/8	1200	-	2
15	"	"	Ditto	RT	-	1
16	"	"	"	-	1300-1400	1
16a	"	"	"	-	1100-1200	1
17	A537	1/2	None	-	-	2
18	Ditto	Ditto	7/16	1200	-	2
19	"	"	Ditto	RT	-	1
20	"	"	"	-	1300-1400	1
20a	"	"	"	-	1100-1200	1
21	A441	1/2	None	-	-	2
22	Ditto	Ditto	7/16	1200	-	2
23	"	"	Ditto	RT	-	1
24	"	"	"	-	1300-1400	1
24a	"	"	"	-	1100-1200	1
25	ABS-B	1/2	None	-	-	2
26	Ditto	Ditto	7/16	1200	-	2
27	"	"	Ditto	RT	-	1
28	"	"	"	-	1300-1400	1
28a	"	"	"	-	1100-1200	1

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13. ABSTRACT

The suitability of flame-straightening methods now used on conventional ship steels for the higher strength ship steels is questionable. This report discusses some of the potential problem areas that need evaluation to examine this subject. Based on a survey of pertinent literature it is shown that only limited data applicable to this subject are available. The data analysis covered the nature of distortion, flame-straightening techniques, and the effects of both single and combined thermal cycles and plastic strain cycles on material properties. An experimental program is presented that is designed to generate background data on conventional steels and several higher strength steels directly pertinent to flame straightening. These data will subsequently be evaluated to ascertain suitability of the flame-straightening procedure for various ship steels.

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