Elevated Temperature Weldment Behavior as Related to Nuclear Design Criteria

characteristics of welded joints are reviewed to show that safety factors could be improved if more data on weld metal and HAZ properties were known

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ABSTRACT. Factors affecting the physical and mechanical properties of weldments are reviewed. Data are presented that show wide variability in the properties of weld metal and heat-affected zones, both within a given weldment and from weldment to weldment. The weld metal or heat-affected zone may be stronger or weaker, and more or less ductile than the base metal joined. This implies that current design rules, which are presumed to have well-known safety factors based on the properties of base metals, may have other actual safety factors in welded construction, due to the differences between weld metal and base metal properties. Some suggestions for obtaining further data that can subsequently be used to improve confidence in design rules or to change design rules for nuclear application are presented.

Introduction

Fabrication procedures require the application of welding processes in the construction of nuclear power plants and components. It is generally recognized that the mechanical and physical properties of a weldment can differ significantly from those of a base metal with a similar chemical composition. Further, the zones within a weldment (base metal, heat-affected zone, and fusion zone) can vary even more significantly than the gross base metal-weldment differences would imply. There is a dearth of design oriented information regarding the behavior of the various zones of a weldment. The metallurgical and structural complexity of welds tends to deter complete analyses of the behavior of weldments.

Current design practice was developed to guard against failure of welds through the use of safety factors on stresses and strains and by requiring that welds be located in regions of relatively low stress. The use of welded construction for nuclear plants at elevated temperatures, where time-dependent deformation can occur under possibly novel service conditions, presents new problems. Better understanding of the behavior of welds may contribute to confidence in the conservative nature of design practice and may lead to relaxation or tightening of safety factors.

The scope of this document is limited to the mechanical and physical properties of welds and weldments and their implications for design of nuclear components and structures intended for elevated-temperature operation. It is not a complete review of the literature nor a data presentation paper, but rather a survey of some important problem areas. No attempt is made to consider the production and certification of weld materials or welds. We intend to summarize the understanding of weld behavior and to present certain recently obtained data that may be applicable in the design of welded components for nuclear primary containment systems.

Variables Governing Weldment Properties

The material and process variables that influence the physical and mechanical properties of a weld are frequently interdependent, so that a change in one variable produces important changes in other variables. For this reason, it is usually difficult to isolate the effects of a single variable on the properties of deposited weld metal. Data obtained from one weldment are likely to be only partially applicable to another weldment made under slightly different conditions. Following is a brief description of five major categories of variables that govern weldment properties.

Material

Chemical composition strongly influences the elevated-temperature properties of welds; the importance of composition has been demonstrated in single phase austenitic weld metal (Ref. 1), and it is equally important in multiphase welds. Although the filler metal nominally dictates the composition of weld metal, base metal dilution, fluxes, and cover gas all contribute to the final deposit composition. Relatively wide limits are permitted in the chemical composition of

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a given grade of filler metal, of the base metal, and of the subsequent weld deposit.

Physical and mechanical properties of starting materials can also be significant. Thermal properties govern the temperature profiles that occur during welding, while the strength properties at temperature affect the distribution of stresses and strains induced during welding.

Joint Design

The geometry of a joint partially determines the welding procedure and hence the thermal and mechanical history of a weldment. Different joint configurations generally lead to different residual stress patterns, structures, and properties in welds. The particular stress and strain distributions that develop under the stress and environmental conditions imposed in service are strongly dependent on the shape of the weld cross section. In addition, the importance of joint design in obtaining sound, acceptable welds has been demonstrated in practice.

Welding Process and Welding Parameters

The gas tungsten-arc (GTA), gas metal-arc (GMA), shielded metal-arc (SMA), and submerged arc (SA) welding processes are most commonly employed for joining nuclear components. These processes can produce welds of substantially different metallurgical structure and properties (Ref. 2). Even within a given process, welding parameters and techniques vary widely. These include such factors as current, voltage, travel speed, electrode size, number and sequencing of passes, the amplitude, frequency, polarity, and shape of the applied voltage and ensuing current pulses, position of welding, and skill or dexterity of the welder. Changes in any one of these interdependent variables can modify the resulting structure and properties of a weld.

External restraints influence the local stress and/or strain patterns that arise during welding. Residual stresses in a finished weld should be considered in the analysis of the behavior of a weld under externally imposed loads. Postweld heat treatment is frequently employed to reduce the magnitude of residual stresses and to temper transformation products in some materials; these treatments are required for thick section ferritic materials.

Postweld Heat Treatment and Elevated-Temperature Service

Postweld heat treatment can, depending upon the times, temperatures, and materials involved, cause changes in the structure, residual stresses, and properties of weldments. Welds that operate in an unstressed condition at elevated temperatures are thermally aged; this can result in improvement or degradation of mechanical properties, depending on material and thermal conditions.

Weld Soundness

Although weld soundness results from the interaction of all the variables listed above, soundness is a variable in its own right that influences the performance of a weldment. Defects such as inclusions, porosity, shrinkage defects, and incomplete fusion are built-in discontinuities that may propagate and cause failure under stresses generated in service. The presence of such defects may reduce the apparent strength and/or toughness of a weldment, lead to premature creep failure, or cause failure after fewer cycles of fatigue loading than would be required to cause sound metal to fail (Ref. 3).

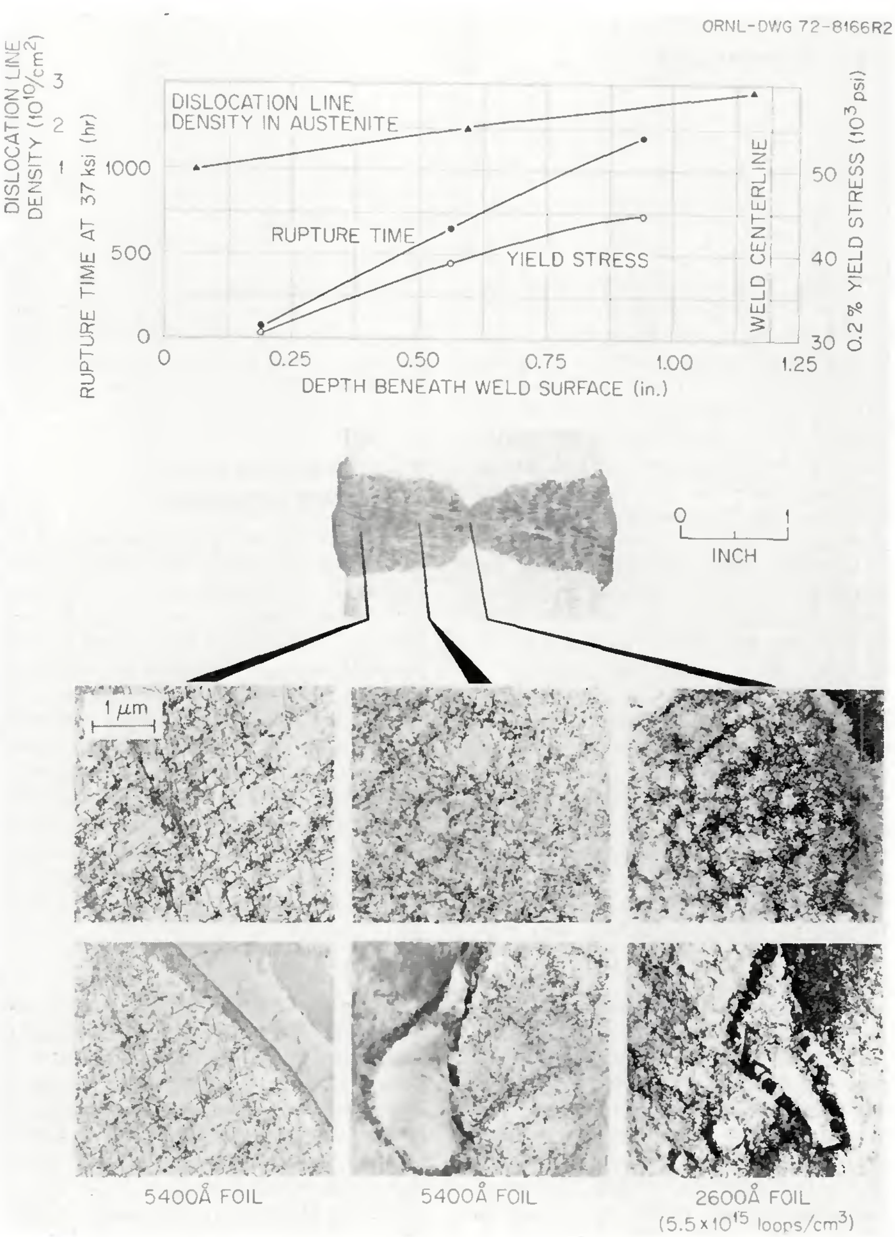

Fig. 1 — Systematic variations of microstructure, creep, and tensile properties of a shielded metal-arc type 308 stainless steel weld with controlled residual elements (CRE). Tests at 1100 F (593 C)

Weld Properties and Performance at Elevated Temperatures

To properly and completely account for the behavior of a weld in service, several kinds of physical and mechanical property data are needed. Many of the desired data are not currently available in the literature, and consideration of the variables

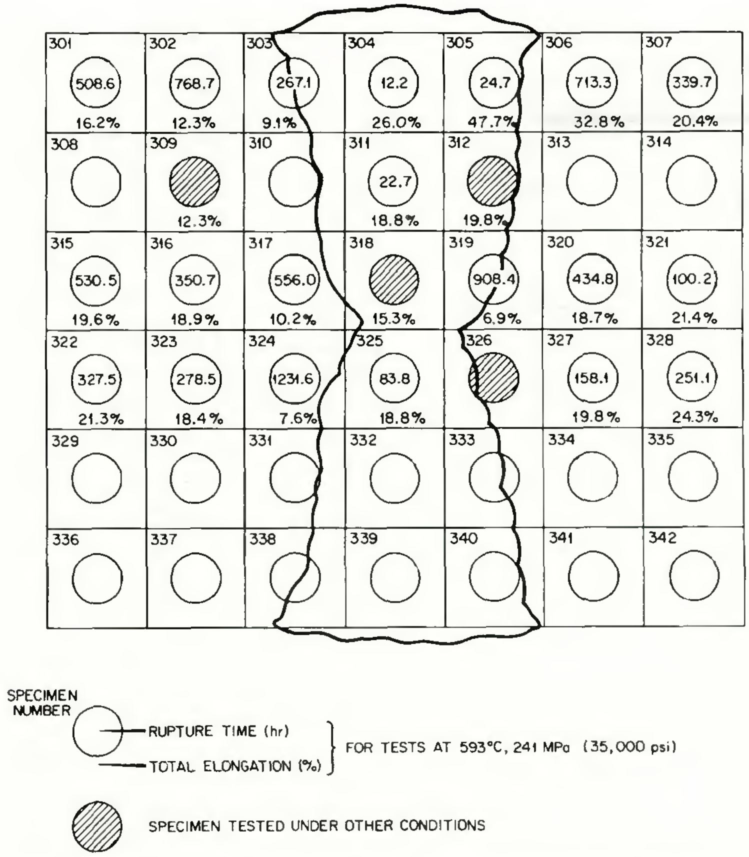

Fig. 2 — Map of rupture times and total elongations for type 308 CRE stainless steel weld metal and type 304 stainless steel base metal tested at 1100 F. Hourglass-shaped region represents weld metal

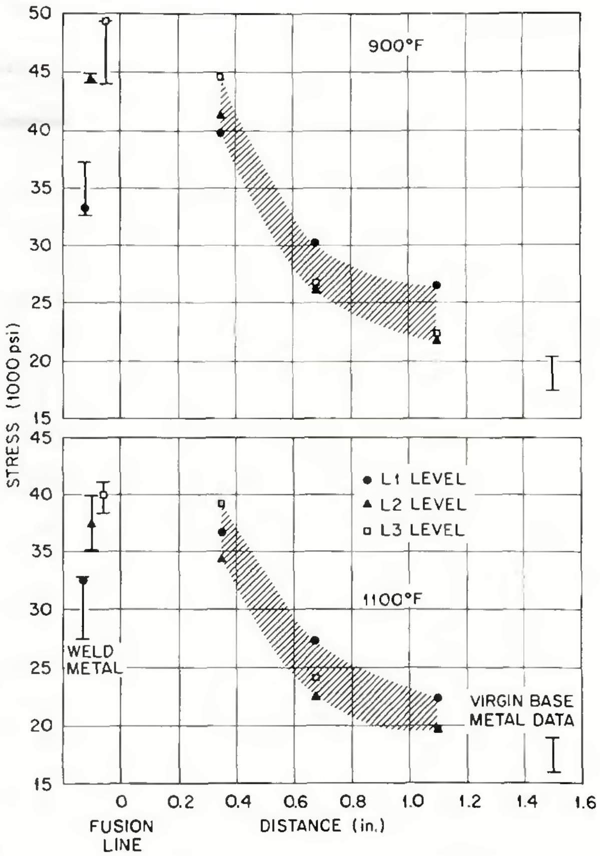

Fig. 3 — Change in 0.2% offset yield stress in a type 308 CRE stainless steel weldment in type 304 stainless steel base metal. Note the variation over a 1 in. long region of heat-affected zone

discussed above warns against the indiscriminate use of data except for well characterized welds, preferably nearly identical to those under consideration. The kinds of data mentioned below are similar to data presently deemed desirable for the use of base metal at elevated temperatures. In the absence of these data, the designer is forced to use methods similar to those currently employed.

The stress-strain-time relationships from tensile and creep tests are required for both tension and compression loading. Stress relaxation and cyclic deformation behavior are necessary for realistic evaluations of deformation in weldments. Conventional fatigue studies should be augmented by crack initiation and subcritical crack growth studies at elevated temperatures. Effects of multiaxial loading conditions should be characterized. Information on the presence of residual stresses and their effects is highly desirable.

In addition, the physical properties of the weld can influence behavior during thermal cycling, and possible interactions with the environment (mass transfer, corrosion, and general compatibility considerations) must be explored and satisfied for the operating conditions of the weld. For welds that are exposed to a neutron or radiation environment, the effects of neutron fluence, flux, spectrum, and irradiation temperature on properties should be considered. The thermal service environment may influence annealing and aging reactions, which can affect properties. Such data are not available for most weld metals, nor are the interactions of the above mentioned variables with these factors generally well established. Thus the designer may not be in a position to deal with these problems at the present time.

The preceding discussion is quite general and it applies to most kinds of welds. However, because of the incipient use of certain austenitic and ferritic materials in reactor components for elevated temperature service, some special considerations for these materials will be given, based on relatively recent investigations.

Weldments of Austenitic Alloys

This section is devoted to welds made in types 304 and 316 stainless steel, Ni-Cr-Fe, and Ni-Cr-Mo-Fe alloys in which both base metal and weld metal are predominantly austenitic. Welds of austenitic stainless steels can contain substantial amounts of other phases. The most frequently observed second phase is ferrite, while martensite, carbides, and other phases may also be present. Further, the metallurgical structures of the welds are not necessarily stable at the service temperature. Sigma, a Cr-Fe ordered phase, can form in service, drastically altering the elevated temperature ductility and the room temperature toughness of the weld metal. There is presently no known way to use short term data to predict the degree to which a given weld metal will be embrittled at elevated temperatures by sigma phase. Ductilities of 1% or less are reported for creep-rupture tests on some welds made in types 304 and 316 stainless steel base metal (Ref. 4). Although weld metals that have better ductility are being developed, the designer should be aware of possible low ductility in welds made with some currently (Refs. 4-6) available commercial filler metals.

Welds vary considerably in their strength and creep-rupture properties (Refs. 4-6). Reasons for these variations are discussed below. Weld metal can be either stronger or weaker than base metal, depending on the materials, test conditions, and other factors such as those discussed above. Therefore, sweeping general comparisons should not be made, but, whenever possible, data for design purposes should be obtained on welds that are similar to or prototypes of those intended for service.

Heterogeneity of the properties and structure of austenitic welds can arise from several sources. An example of heterogeneity is shown in Fig. 1, in which a type 308 stainless steel filler metal was used to join type 304 stainless steel plates (Ref. 6). An examination of this weldment showed that microstructure, yield strength, and creep properties varied systematically through the thickness of the weld. The variations in this case arose from local differences in thermomechanical history and can be semiquantitatively related to the dislocation structure of the austenitic phase. In addition, the base metal near the weld was subjected to thermal and mechanical cycling during welding, and local changes in microstructure and mechanical properties have occurred.

An example of the effects of thermomechanical cycling on the type 304 stainless steel base metal (from the weld shown in Fig. 1) is given in Fig. 2. Specimens of base metal from near the weld and composite longitudinal specimens of base metal and weld metal exhibited different creep behavior than base metal specimens from an unaffected region away from the weld. The elevated temperature tensile yield strength in the heat-affected zone in the example was nearly twice the monotonic yield strength of the as-received base metal (Fig. 3). Another example shows that weld metal can be softer than base metal under certain conditions. The hardness traverse of an Incoloy 800 autogenous weld shown in Fig. 4 illustrates that a fused region

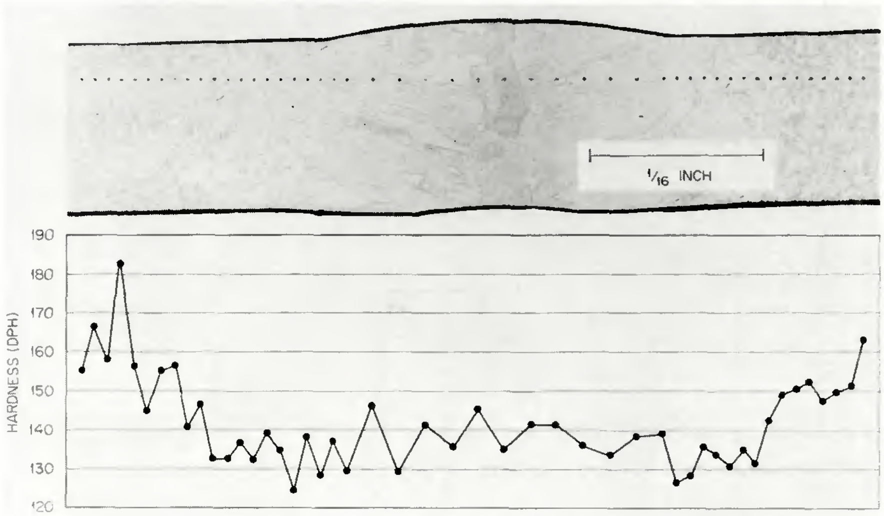

Fig. 4 — Diamond pyramid hardness traverse across an autogenous weld in Incoloy 800

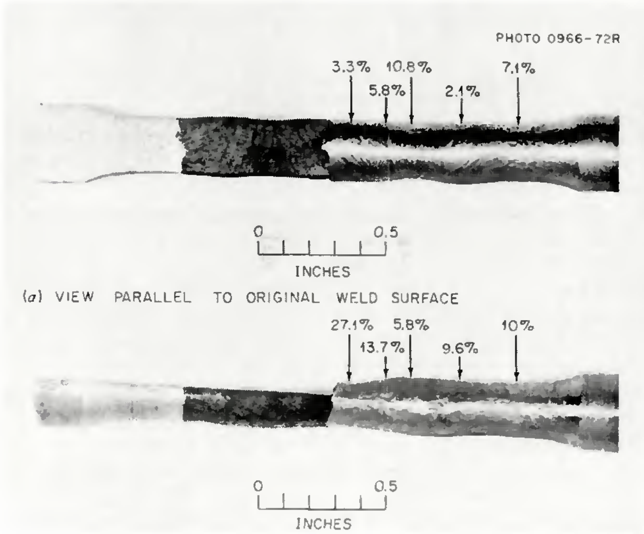

Fig. 5 — Two views of the gage section of a transverse weld specimen pulled at room temperature. The left piece has been cut, polished, and macroetched to reveal weld metal and base metal. The pieces are shown with a 180 deg relative axial rotation

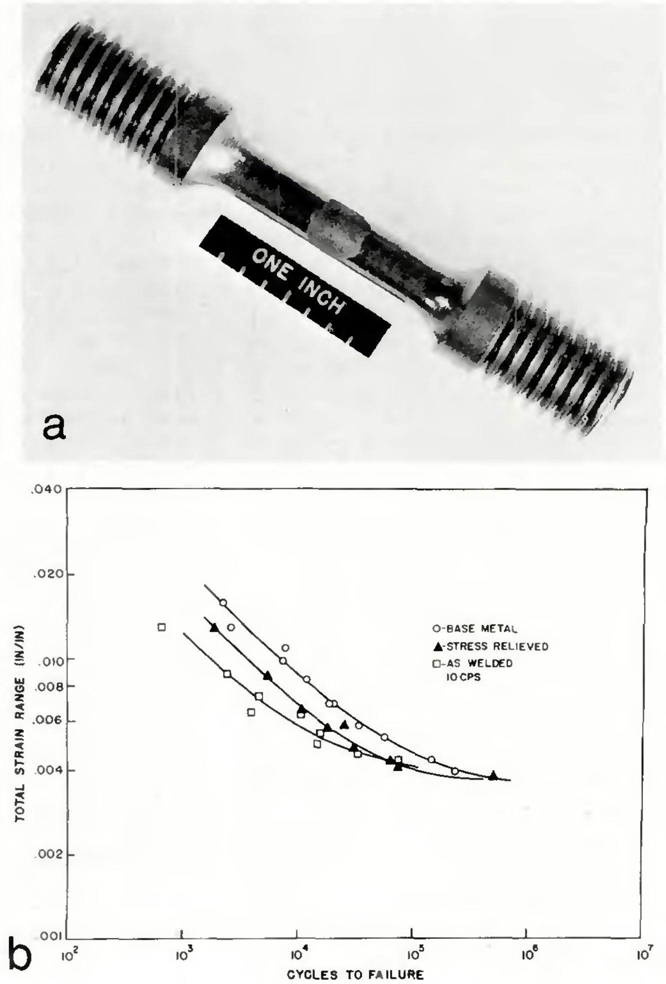

Fig. 6 — Comparison of the room-temperature fatigue properties of type 304/308 stainless steel weldments and base metal tested in displacement control. (a) Specimen details. (b) Room-temperature data

need not always be stronger than base metal.

Anisotropy of elastic and plastic deformation has been demonstrated in an austenitic stainless steel weld (Refs. 6,7). This may cause severe changes in deformation behavior at the fusion line, resulting in local stress and strain concentrations at and near the fusion line. In addition, the orientation of the principal axes of anisotropy may vary. Figure 5 illustrates severe anisotropy of deformation in two views of a transverse weld specimen from the weld shown in Fig. 1.

The implications of these findings reinforce the stated need for careful consideration of the source of weld metal data and for documentation of the weld history and the manner in which the tests are performed. Local property variations and effects of anisotropy make test results quite sensitive to the testing manner.

Cyclic deformation and fatigue behavior are influenced by the presence of welds (Refs. 8-10). Weldment geometry, configuration of associated base metal components, defects, and assembly restraint are generally the most important parameters affecting weldment fatigue. Characteristically, fatigue cracking involves comparatively little gross plastic deformation and usually develops in regions of high stress concentration. Gurney (Ref. 11) compared the fatigue strength (2×10^6 cycles) of several joint types with mild steel base metal and found that the fatigue strength of the weldment was always inferior to that of base metal, although some joints were better than others.

The influence of residual stress level on weldment fatigue behavior is controversial. Some investigators report (Ref. 10) little effect of stress relief and others report (Ref. 9) a significant influence. Residual tensile stresses normal to the major axis of a flaw are generally felt to be harmful, but to an extent that may depend on the ratios of the principal stresses in loading (Ref. 9).

James (Refs. 12,13) recently reported crack growth rates in weldments of type 304 stainless steel with type 308 filler metal that were prepared by GTA, SA, and SMA weld processes. He found no influence of weld process on the elevated temperature low-stress subcritical crack growth rates. Further, crack growth rates in welds were no greater than those in base metals.

The complexity of welds and the costs of testing fairly large specimens in order to assess geometric effects have contributed to the lack of data and understanding of weldment behavior. This is particularly true for low cycle fatigue performance, and only limited data are available for LMFBR structural material weldments (Ref. 14). The available data were obtained from small specimens taken from various weld metal, heat-affected zone, and base metal regions. Because of the lack of definitive data, general comparisons of the various weld zones are of questionable value at present.

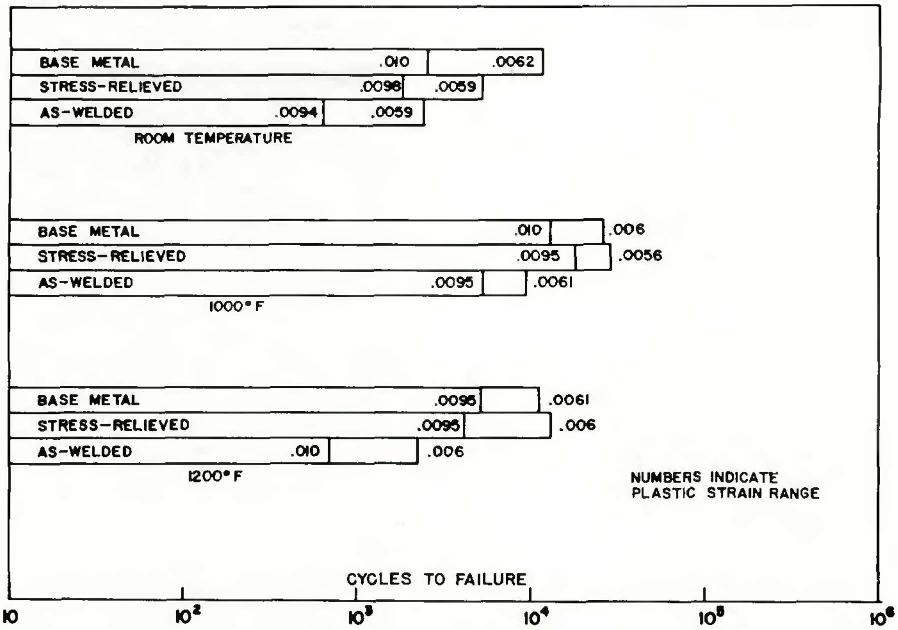

Fig. 7 — Comparative fatigue life of base metal, as-welded, and welded-plus-postweld-heat-treated weldments

Composite data for various joint designs are scarce. Fatigue testing of weld materials is in progress at Aerojet Nuclear Company and the Argonne National Laboratory.

Swindeman and Canonico (cited by Gilliland, Ref. 5) performed low cycle fatigue tests on uniform-gage specimens, shown in Fig. 6(a), containing small V-groove welds of type 308 stainless steel weld metal together with base metal and heat-affected zone. At room temperature for some strain ranges weldment specimens had about one-fifth the low cycle fatigue resistance of base metal control specimens [Fig. 6(b)]. Cracks initiated in the base metal heat-affected zone, where strains were concentrated. At 1000 and 1200 F (538 and 649 C) in vacuum (2×10^{-7} torr, 3×10^{-5} Pa), weldment fatigue resistance was inferior to that of base metal; cracking initiated in the base metal heat-affected zone at 1000 F and in the weld metal at 1200 F. A post-weld heat treatment improved the elevated temperature fatigue life of weldment specimens, in which cracks initiated in the weldment (Fig. 7). Postweld heat treatment of the weldment for 1 h at 1300 F (700 C) before testing was beneficial.

Hayes and Vandergriff (Ref. 14) tested tubular specimens taken from SMA and SA type 308 stainless steel welds in the transverse and longitudinal directions and compared their creep-fatigue behavior with type 304 stainless steel base metal. The electrodes used in the SMA welds were identical to the controlled residual element (CRE) filler metals mentioned above. The base metal was from two heats used in nuclear construction. The authors concluded from six tests at 1050 F with a 28.5 min tensile hold time that the SMA CRE weld had greater resistance to low cycle creep fatigue interaction than base metal, since cracks initiated in the base metal and propagated into the weld metal. The cracks in SA welds initiated in the weld metal and propagated into the base metal, and the SA welds were therefore judged to be more susceptible to creep-fatigue damage than either the base metal or CRE SMA weldment.

Brinkman et al (Ref. 7) conducted low cycle strain-controlled fatigue tests on the same CRE 308 weld metal used in the study of Ref. 6. Uniform-gage specimens were taken from various positions within the weldment in the transverse and longitudinal (parallel) orientation; base metal, weld metal, and fusion line gage sections were made where they were appropriate. Tests were conducted at room temperature and 1100 F (593 C), using a longitudinal extensometer to measure and directly control the strain over the 0.375 in. (9.47 mm) gage length. Longitudinal and diametral strain

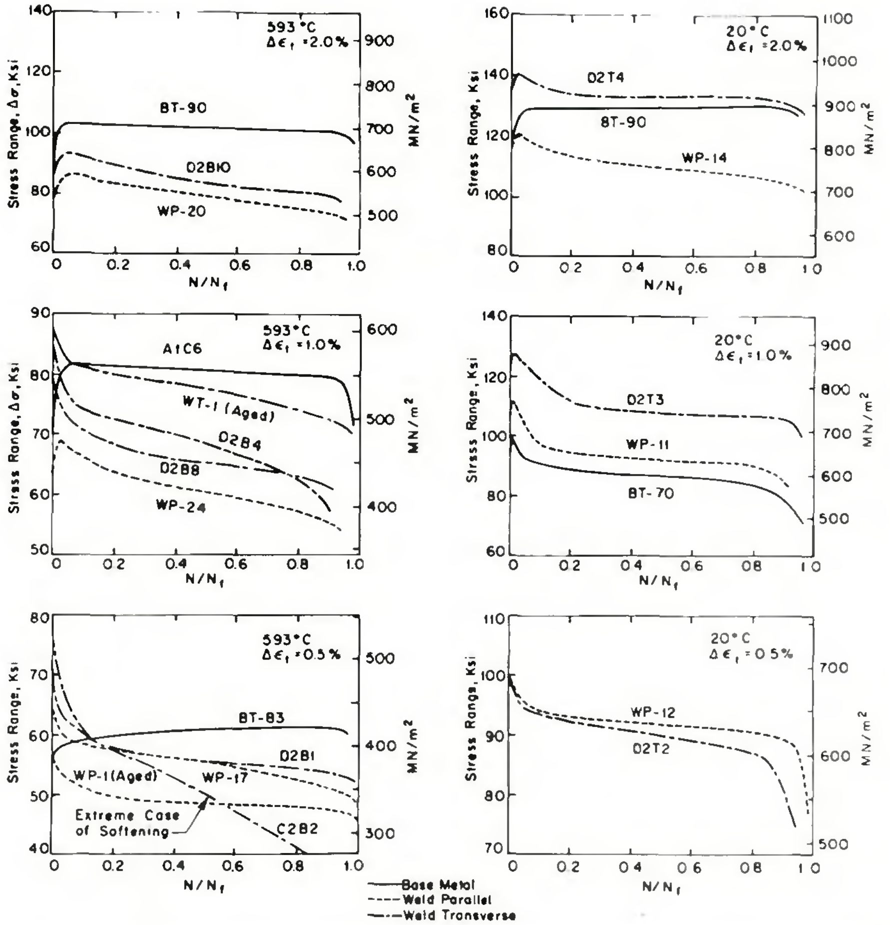

Fig. 8 — Stress range vs fraction of fatigue life in strain-controlled fatigue tests of type 304/308 stainless steel SMA weldments tested at room temperature (20 C) and 1100 F (593 C)

measurements showed considerable variation in Poisson's ratio and Young's modulus within the all-weld-metal specimens.

In Fig. 8 the measured stress range is plotted as a function of fraction of cyclic life for these strain range controlled tests. The base metal cyclically hardened during the initial portion of the test and then stabilized until cracking occurred, but the weld metal hardened for only a cycle or two and then usually softened throughout the remainder of the test. Total strain range is plotted against cycles to failure in Figs. 9 through 11. The influence of tensile hold times and irradiation on the cyclic life of weld metal (CRE), taken from several orientations and positions within the weldment, are compared to that of base metal in Fig. 12. The elevated temperature fatigue data given in Figs. 9, 11, and 12 indicate a considerable effect of orientation and position within the weldment on fatigue and creep-fatigue lifetimes, with both increases and decreases in fatigue resistance possible with respect to base metal. Irradiation to fluences where changes in mechanical properties begin to occur results in a decrease in the low cycle (ductility dominated) fatigue life of weld metal, but may actually increase the high cycle (strength dominated) resistance when creep effects are not important, as shown in Fig. 11. Irradiation may also decrease creep-fatigue resistance; however, the extent to which this may occur is orientation dependent, as shown in Fig. 12.

At low strain ranges where strain is essentially elastic the results of this study lead to the tentative conclusion that the failure performance of the weld metal may approach that of the base metal (Figs. 9 and 10). Since the strength of this weld metal is comparable with or superior to that of the base metal, and since strength is usually considered to be the governing material property under elastic loading conditions excluding stress concentrations and residual stresses, similar fatigue properties might well be expected. Shahinian (Ref. 15) and James (Ref. 13) have reported that resistance to subcritical crack growth under essentially elastic loading is similar in base and weld metal (Fig. 13). Aging of several specimens for periods up to 1000 h at 1100 F (590 C) did not significantly influence the low cycle fatigue resistance of weldment material at room temperature or 1100 F.

The impact properties of austenitic steel welds can be different from those of base metal. Hawthorne and Watson (Ref. 16) have reported austenitic stainless steel weldments to have lower energy absorption than base metal. Shielded metal-arc weld deposits had higher notch ductility than submerged arc weld deposits.

Welds of Ferritic Steel

The ferritic materials can be categorized in two groups, (1) nonheat treatable classes, grades that behave similarly to the austenitic materials, and (2) heat treatable classes, grades whose mechanical properties can be drastically changed by preservice thermal processing, such as 2¼ Cr-1 Mo steel.

The nonheat treatable ferritic weldments (e.g., the completely ferritic type 446 stainless steel) are processed similarly to an austenitic material. Two important factors must be considered for nonheat treatable ferritic alloys:

1. They are susceptible to embrittlement in the temperature region near 885 F (475 C).

2. Some austenite may be formed during processing and transform to martensite upon cooling. This is especially true during welding. Consequently these materials are given a postprocessing heat treatment designed to relieve stresses and temper any transformation product that may exist. Because of the similarity between the nonheat treatable ferritic and austenitic materials, we concentrate here on the heat treatable grades of ferritic materials.

Welds in heat treatable ferritic material can develop nearly the entire range of metallurgical structures possible in the particular alloy in a relatively small heat-affected zone of the base metal. The hallmark of ferritic materials is the wide range of structures and properties that they can have. These materials include the low alloy high strength steels that are commonly employed for structural applications and the more highly alloyed martensitic steels that possess unique high-temperature and/or corrosion resistant properties. The ferritic materials undergo phase transformations, and because of these phenomena, the mechanical properties of heat treatable ferritic materials can be enhanced through thermal processing. These phase transformations can be a disadvantage in welding, where a component is subjected to a range of temperatures from ambient to above the liquidus. A relatively small zone of the base metal is subjected to temperatures that can dramatically influence the mechanical properties of that zone.

Figure 14 provides an example of the temperature distribution in 2¼ Cr-1 Mo steel with 0.11% C for an autogeneous weld (made without filler metal) with a "typical" heat input for a manual welding process. The base metal is heated to maximum temperatures ranging from about 700 F (370 C) to the liquidus in a distance of about 0.15 in. (3.8 mm). This temperature range includes the embrittlement range [about 800 to 1050 F (425 to 565 C) for certain steels], tempering range [about 1100 to 1300 F (590 to 700 C) for certain steels], partial austenitizing range [1300 to 1550 F (770 to 850 C) for certain steels], and full austenitizing range [greater than about 1550 F (850 C) for certain steels].

The effect of the thermal excursion on the base metal is shown in Fig. 15 for a multipass weld in ½ in. thick (12.7 mm) 2¼ Cr-1 Mo steel. The hardness values of the weldment vary from nearly 400 DPH in and near the last pass to about 200 DPH in the base metal. Tempering occurred in the early passes.

A postweld heat treatment is nearly always recommended for ferritic materials; it tends to equalize the hardness values of the weldment. Figure 16 shows the same weld in 2¼ Cr-1 Mo steel with 0.11% C seen in Fig. 15, after a postweld heat treatment at 700 C (1300 F) for 1 h; the highest hardnesses (approx 400 DPH) have been reduced to about 225 DPH. The postweld heat treatment also relieves residual welding stresses, which can be of yield point magnitude.

Welding procedures for ferritic materials usually include preheating to eliminate underbead cracking. The preheat affects the cooling rate, which in turn affects the microstructure of both the base and weld metals.

There is little information on the elevated temperature properties of ferritic weldments. Some tensile data are available (Refs. 17-20), but the weld metal was usually not well characterized. Little attention is paid to the heat-affected zone other than the concern shown for underbead cracking. Ferritic weld metal usually has a higher ratio of yield strength to ultimate tensile strength and lower ductility than base metal, even at elevated temperature. This generalization, of course, depends on the thickness of material under consideration, its heat treatment, and the welding process and parameters employed. High heat input welds in heat treated thin sections of ferritic base metals can result in a weaker weldment, but such applications are rare.

The impact properties of welds in ferritic steels can differ from those of base metal. Hawthorne (Ref. 21) reports that transition temperatures in certain welds are higher than those for base metal plates or forgings.

The creep properties reported for ferritic welds are frequently not for well characterized materials (Ref. 20). Ferritic weld metal can have either higher or lower strength and/or ductility than weld metal, depending on factors discussed above (Ref. 20). In a study of transverse weldment specimens conducted at ORNL (the gage length of the specimen contained base metal, heat-affected zone, and weld metal) failure occurred in the base metal.

The information available on the fatigue behavior of ferritic material at elevated temperatures appears to be scant. There is evidence (Ref. 22) that the fatigue properties of ferritic materials may be impaired by con-

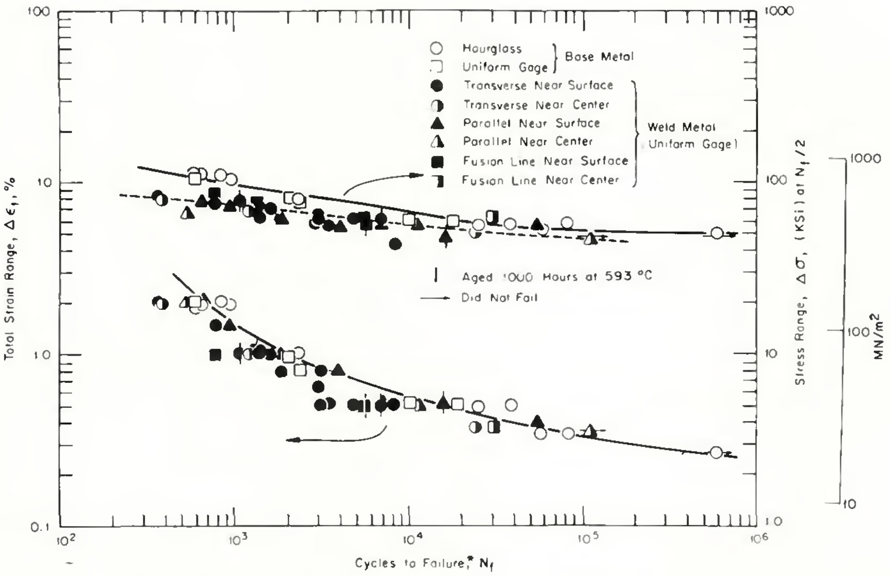

Fig. 9 — Total strain range and stress range vs cycles to failure for specimens taken from several positions within an SMA type 304/308 stainless steel weldment and base metal tested at 1100 F (593 C). Failure is defined as 50% decrease in tensile stress accompanied by gross cracking for uniform-gage specimens

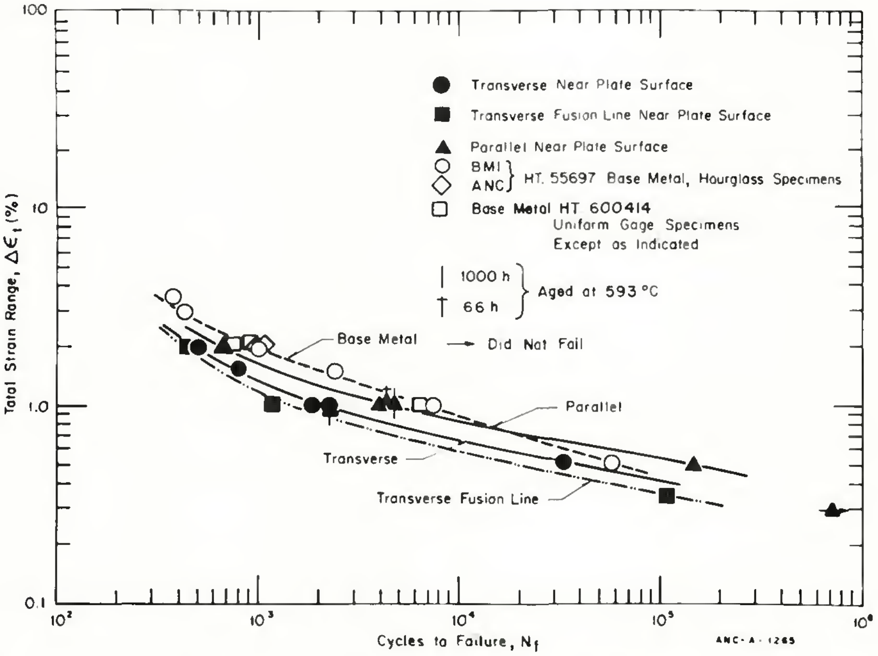

Fig. 10 — Total strain range vs cycles to failure for specimens taken from several positions within SMA type 304/308 stainless steel weldments and base metal at room temperature

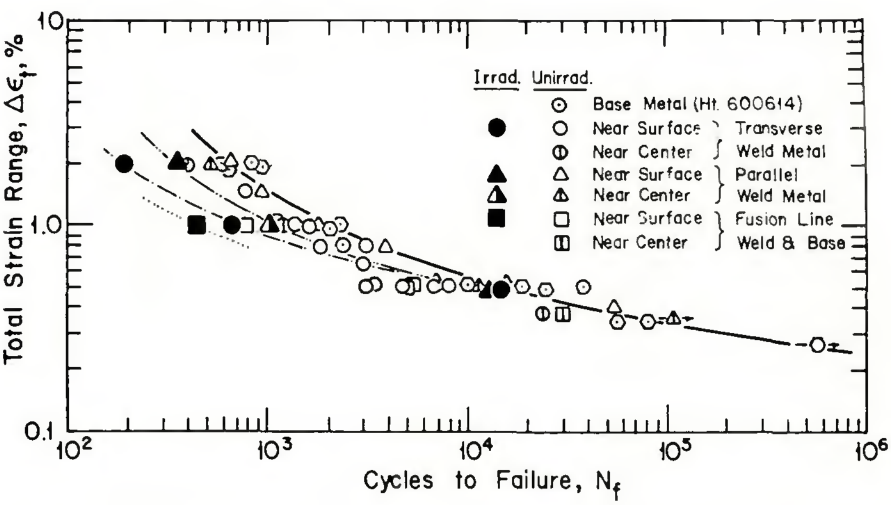

Fig. 11 — Comparison of the low-cycle fatigue behavior of type 308 stainless steel weld metal in the irradiated [0.5 to 1.0 × 10^{22} n/cm² (>0.1 MeV)] and unirradiated condition. All tests were performed at a strain rate of 4 × 10^{-3}/s at 1100 F (593 C)

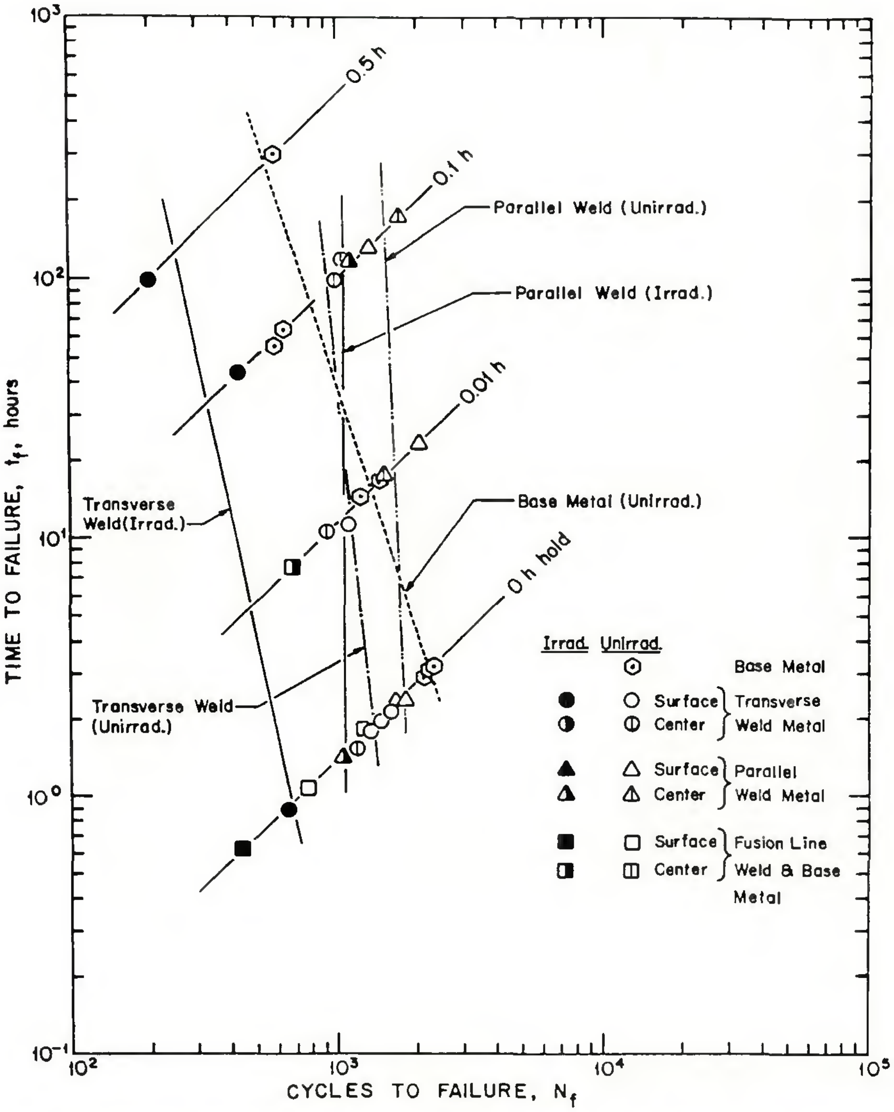

Fig. 12 — Time to failure as a function of cycles to failure and tensile hold time for irradiated and unirradiated type 308 weld metal tested at 1100 F (593 C) at a total strain range of 1.0%. Fluences were 0.5 to 1.0 × 10^{22} n/cm² (>0.1 MeV)

current thermal cycling in the range from 570 to 850 F (300 to 450 C) during cyclic stressing. The degree of this effect depends on microstructural factors. The loss of fatigue life appears to correlate with the reported (Ref. 23) temperatures at which temper embrittlement can occur in low alloy steels.

The lack of data on welds in ferritic material justifies penalities for the use of welds for elevated temperature service.

Interfacing Materials Properties and Design Considerations

It is realized that there are presently only limited requirements for design of welded nuclear components for elevated temperature service. This paper is intended to indicate areas that can be strengthened by further consideration. Nuclear equipment manufacturers who are in a position to implement improvements in design methods or to add to available data are encouraged to do so whenever possible.

Neither Sect. III of the *ASME Boiler and Pressure Vessel Code* nor *Code Case 1331* presently contains properties or allowable stresses for weld metal or for weldments. In vessels designed according to Sect. III of the *ASME Boiler and Pressure Vessel Code,* the safety factors in the code are intended for the entire pressure boundary. However, failures at weldments are not uncommon (Ref. 24), and they may be indicative that certain safety factors originally based upon *base metal* properties may not be wholly adequate under all conditions when welds are present.

In piping systems designed according to Sect. III of the *ASME Boiler and Pressure Vessel Code,* stress indices of NB-3680 provide additional safety factors for certain types of welded construction. However, NB-3681 permits justifiable reductions of these safety factors; hence, better understanding of weldment behavior might lead to a relaxation of safety factors and concomitant cost benefits.

At temperatures where time-dependent deformation is considered, *Code Case 1331* provides certain restrictions on welds. It also provides a safety factor for the presence of welds by requiring strains in welds to be limited to one-half the allowable strains in base metal. However, base metal properties are used to calculate strains occurring in regions of weld metal, an approach that is convenient but not necessarily realistic. This approach may result in an unpredictable degree of conservativeness.

This paper differs from Sect. III of the *ASME Boiler and Pressure Vessel Code* and from *Code Case 1331*

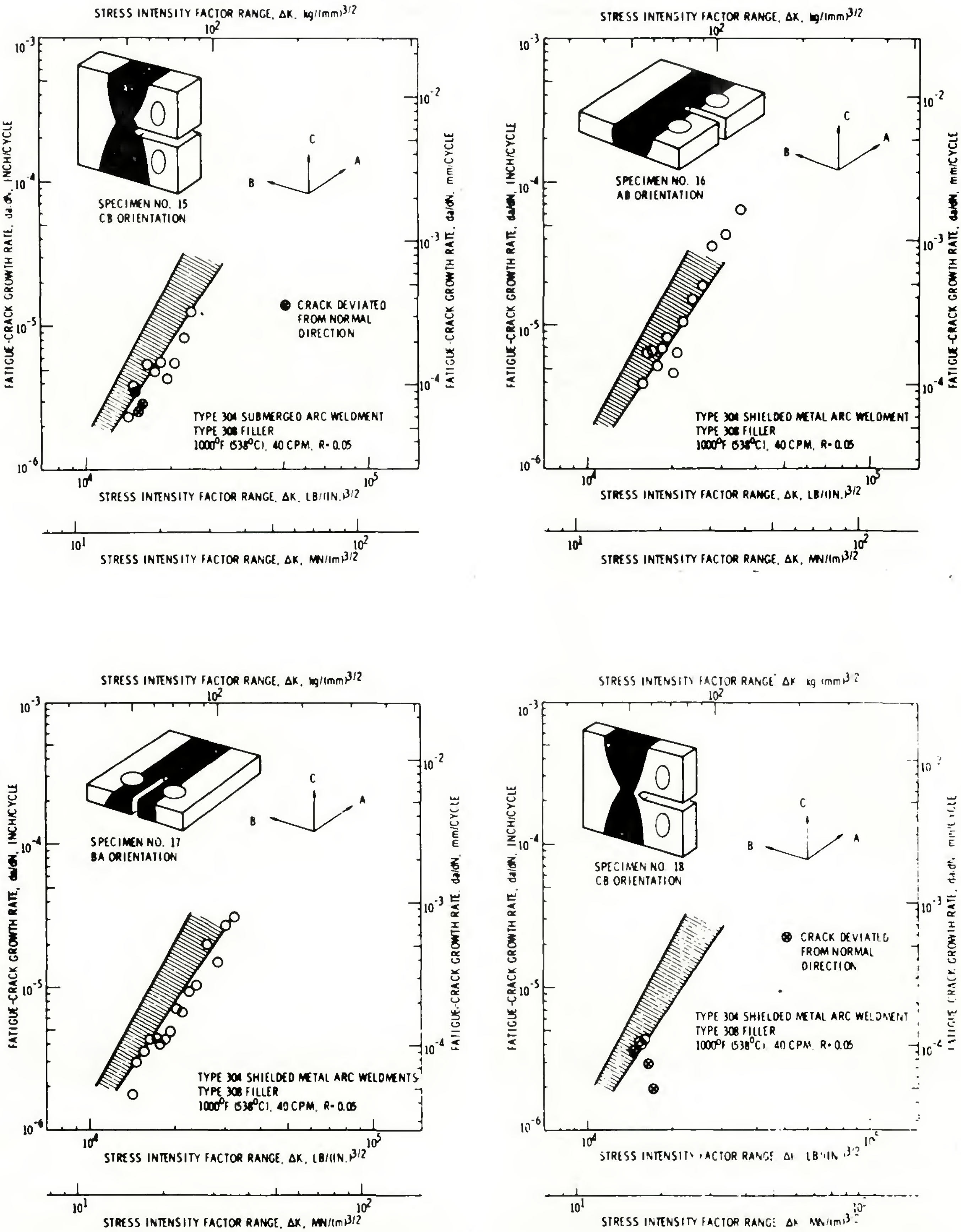

Fig. 13 — Fatigue crack propagation behavior of type 304 SA and SMA weldments tested at 1000 F (538 C). Shaded area represents base metal behavior

primarily in recognizing the differences between the mechanical and physical properties of weld metal, base metal, and combinations thereof. No attempt is made to alter the rules governing the materials, fabrication, and examination of welds. Clearly, information concerning weld metal and weldment physical and mechanical properties is necessary. Currently, however, such data are not available for all the commonly used weld metals. In the absence of this information, the designer has little recourse but to use the existing design codes and mandatory standards. Applicable data for a broad spectrum of welds is not to be expected for some years. However, certain types of welds are presently under intensive study, and as the data become available, the designer should make every effort to utilize them to advantage.

As appropriate data become available, the manner in which these data are to be applied is not clear. Two fundamentally different philosophies are proposed as extremes.

The first is based on a simplistic approach. It requires that the average (or minimum, or trend band) properties of weld metals and heat-affected zones be equal to or better than some fixed fraction of the corresponding identical property of the base metals. This approach might be used in conjunction with existing design rules or modification thereof. The advantages of this approach are relatively low initial expense and simplicity. It does not however assure the degree of conservativeness of design that may be desired.

The second approach is longer range and involves analytically and experimentally examining in detail the stresses and strains that occur in and near weldments. "Worst case" geometries, permissible material property mismatches, and service conditions might be examined to develop design rules having more accurately known safety factors. This approach involves relatively high cost, a relatively long time implementation, and the possibility that the rule development process may be complex. The resulting rules themselves may be relatively simple and easy to apply.

Regardless of which approach is taken, certain fundamental data are needed to improve the present situation. The methods of obtaining these data, and the types of data required, may be significantly different than those for base metal.

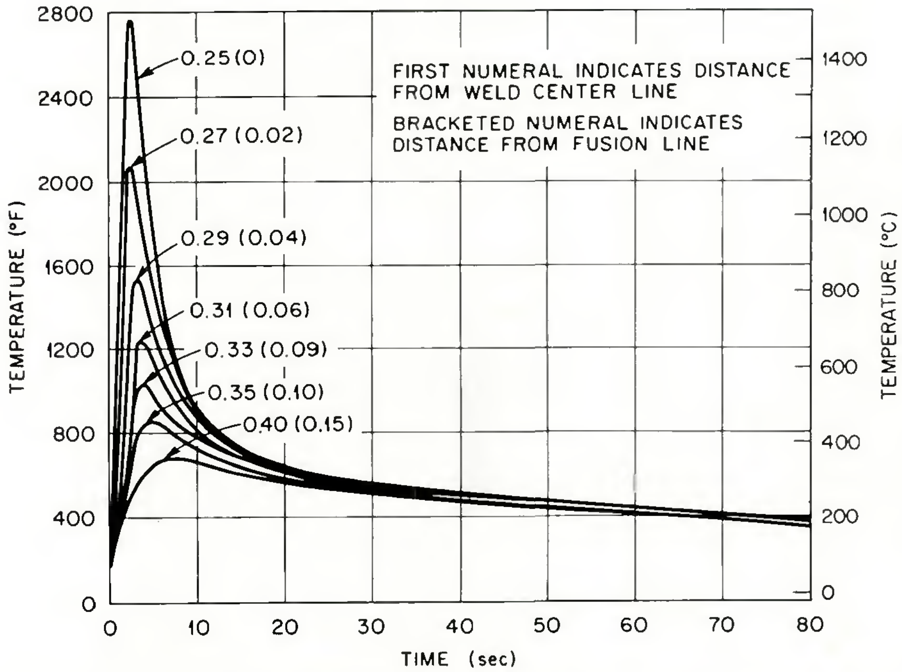

Fig. 14 — Temperature distribution as a function of time and distance for a 27 kJ/in. (1.06 MJ/m) weld in a ½ in. (12.7 mm) steel plate. Distances are in inches (1 in. = 25.4 mm)

Summary

Numerous material and process variables influence the structure and properties of welds at elevated temperatures. Not only are there large variations in properties between different welds, but local variations of most properties within the heat-affected zone and fusion zone of a given weldment contribute to the complexity of the situation. Present design rules for elevated temperature construction penalize the use of welds by restricting them to areas of relatively low stress, by imposing stringent quality control, and by limiting strains in weld metal. However, the differences between weld metal and base metal properties are not formally accounted for, nor are properties or allowable stresses for weld metal given. Applicable data are being developed for some types of welds, and methods for interfacing these data with design methods to assure the desired degree of conservativeness are discussed.

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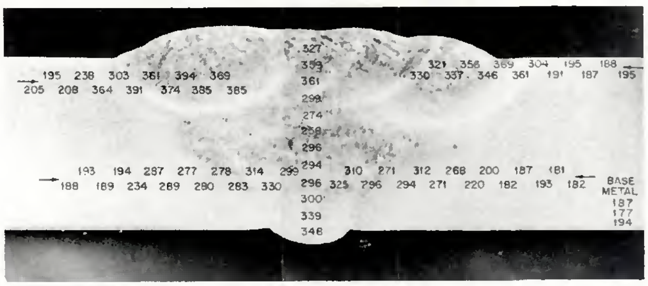

Fig. 15 — Hardness (DPH) traverse of as-welded 2¼ Cr-1 Mo steel with 0.11% C

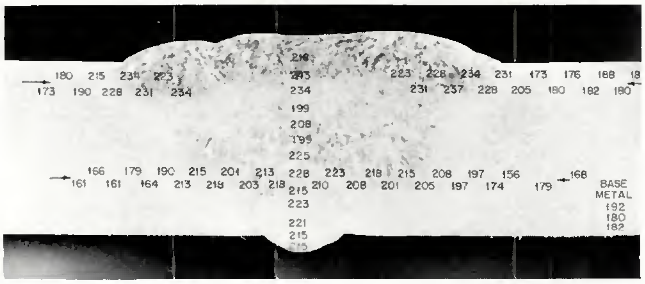

Fig. 16 — Hardness (DPH) traverse of postweld heat-treated 2¼ Cr-1 Mo steel with 0.11% C

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