AMRA MS 65-08

AMRA MS 65-08

THE ROLE OF WELDING IN BRITTLE FRACTURE

MONOGRAPH SERIES

by

WILLIAM P. HATCH

DECEMBER 1965

MATERIALS TECHNOLOGY DIVISION
U. S. ARMY MATERIALS RESEARCH AGENCY
WATERTOWN, MASSACHUSETTS 02172

THE ROLE OF WELDING IN BRITTLE FRACTURE

William P. Hatch

Materials Technology Division

UNITED STATES ARMY MATERIALS RESEARCH AGENCY

December 1965

CONTENTS

U. S. ARMY MATERIALS RESEARCH AGENCY

THE ROLE OF WELDING IN BRITTLE FRACTURE

INTRODUCTION

The welding engineer concerned with the design and fabrication of modern structures cannot avoid recognition that he is deeply involved in the brittle fracture predicament. He soon realizes that his problem is particularly severe because, while there is too little known about the fundamental aspects of brittle behavior in metals, he is expected to apply all of the knowledge that is available to obviate difficulties in a region consisting of a gradient of constantly changing metallurgical structures. His problem is further aggravated by complexities of the welding process itself, complications in the use and control of the process, and difficulties of testing the mechanical and metallurgical properties in the gamut of structures which constitute the weld joint area.

There is no denying the fact that welds are often weak links in otherwise sound structures. There are some inherent characteristics about the welding process that allow inadequate practices or procedures to produce detrimental microstructures, discontinuities, and inhomogeneities that can be of critical size from the brittle fracture standpoint. However, welds are not the only region to be considered as brittle fracture initiators. There is ample evidence presented in the literature to indicate that the history of brittle failures of structures did not originate with the use of welding. Furthermore, weldments have often been unfairly held suspect when unsound practices in other phases of material utilization, design, and production engineering were the prime causes of brittle fracture behavior. Nonetheless, the mere act of making a molten metal weld deposit enhances the possibilities of creating flaws in a previously sound material. The welding engineer's problem is to determine how to hold to a minimum the chance flaws inherent to the process, and insure that such discontinuities as may occur will remain smaller than the critical defect size under the service conditions to which the weldment will be subjected. He must also select procedures to avoid excessive degradation of the base metal properties in the heat-affected zones and at the same time choose a filler metal for depositing welds that will have adequate properties for the intended service.

The purpose of this paper is to survey from a materials standpoint some of the factors associated with welding that can contribute to brittle behavior. The discussion has intentionally been limited to reviewing ferrous metals problems because these materials have historically been the principal ones used in welded constructions. Nevertheless, with expanding use of more sophisticated materials for structural weldments being forecast, the concepts and general principles derived from experience with steel should provide some basic guides to the kind of fabrication controls needed to alleviate progressive problems with brittle behavior in future applications of advanced materials.

BASE METAL FACTORS AFFECTING RELIABILITY

Toughness

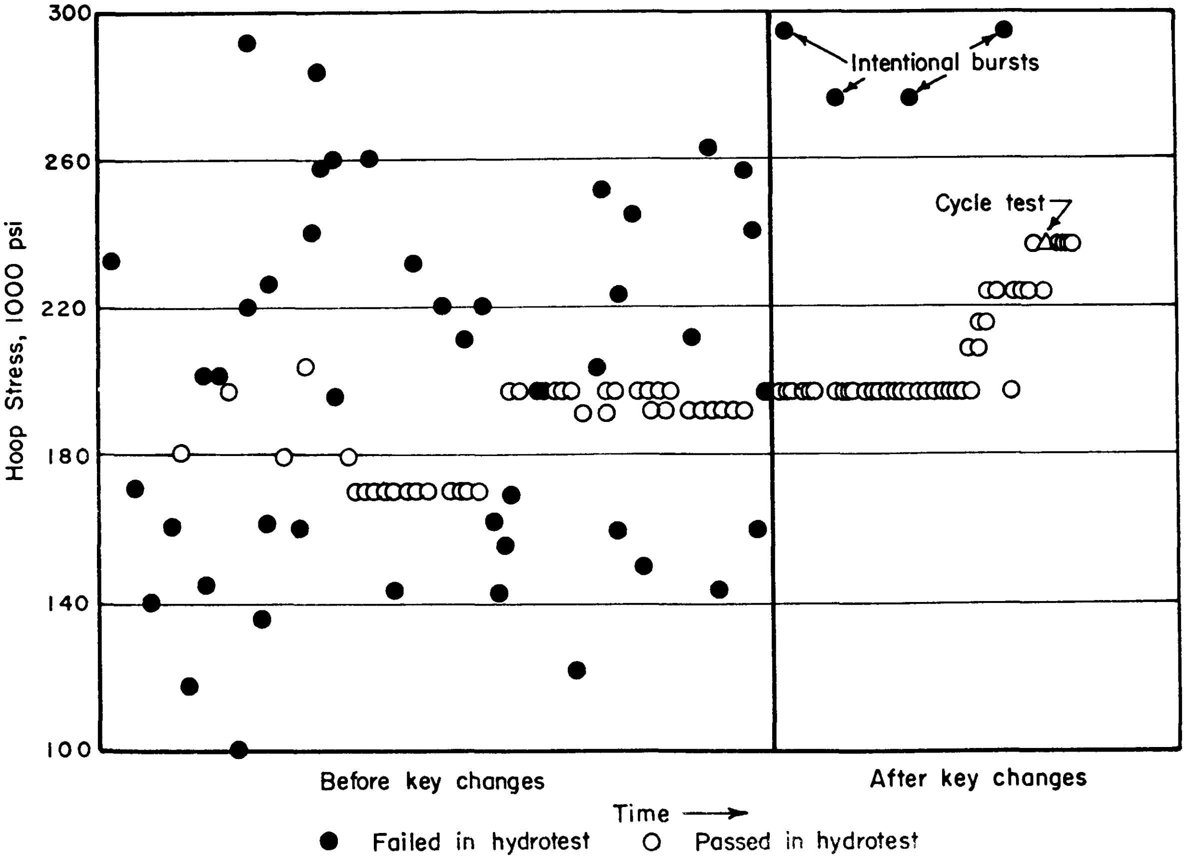
Undoubtedly one of the most fertile areas where improvements in brittle failure prevention can be obtained is in the selection of the structural materials which are to be fabricated by welding. The selection stage is important not only from the standpoint that the basic materials must have good weldability characteristics, but also from the standpoint that tough materials are needed to resist crack growth and rapid propagation. Too often economics and availability considerations overshadow the toughness requirements when specification of the materials for weldments is being made. This, in addition to the fact that other engineering factors take precedence over brittle fracture in design consideration, has major significance in the weldment failure problem.

A review and discussion of selected brittle service failures was presented in Monograph MS-48.* It is interesting to note that of the failures discussed, a large majority were found to have fracture origin sites in welds, yet seldom is evidence presented that brittle fractures propagated in the weld zone. Usually, fractures initiating in the weld zone propagated transversely (or at some oblique angle to the weld axis) through the base metal which was lacking in sufficient toughness to prevent extensive crack propagation. This is a common mode of failure that has been observed in fractured weldments.

Since the weld zone is a region that is intrinsically prone to inhomogeneity and to the existence of chance macroscopic, microscopic, and submicroscopic flaws, one of the best approaches to avoid catastrophic failure is to build the structure with materials which inherently have good notch toughness. At least in this way larger discontinuities can be tolerated. While the problem of selecting materials with adequate toughness may not be resolved easily, two cases can be cited as illustrative of the importance which should be attached to this factor.

Two papers[1,2] summarizing data derived from the extensive studies of ship failures, succinctly point out that by utilizing materials with improved toughness, the ship casualty rate has been reduced to almost zero. One of the most important changes leading to this improvement was introduction of toughness requirements in the specifications covering ship plate steels. The second illustration involves solid-fuel rocket motor case construction. Many evaluation programs have shown that because materials for this application are used at ultrahigh strength levels, they have an intrinsic tendency toward brittleness. Here, finding alternate materials with improved toughness remains a significant problem. Nonetheless, progress is being made. Figure 1 serves as an illustration of what can be done when the problem is recognized and corrective steps are taken.[3]

***Fracture of Structural Metals. U. S. Army Materials Research Agency, Monograph Series WAL MS-48, June 1962.*



19-066-1273/AMC-63

Figure 1. RELIABILITY OF SOLID-FUEL ROCKET MOTOR CASES

REPRINTED FROM DMIC REPORT 173

Initially, large rocket motor cases were fabricated by the roll-and-weld technique. The welded longitudinal seams produced by this technique fell into disrepute. It would have been better to employ only transverse welds to take full advantage of the biaxial stress ratio. Extensive examinations of failed cases showed that most of the failures resulted from either poor welding or inadequate inspection coupled with poor fracture toughness of the steel at the high strength level being used. Nevertheless, considerable effort was directed toward eliminating the weld from future case sections. Cylindrical cases were formed by spinning, deep drawing, and machining ring forgings.[3] These alternate approaches did not provide complete answers to the problem because premature brittle fractures continued to occur.[4] Meanwhile improvements were being made in roll-and-weld techniques. One example of the type of improvement that can be attained has been given for the production of motor cases for the Nike Zeus and Skybolt missile systems.[5] Figure 1 shows the benefits that were obtained when rigid specifications on incoming materials and meticulous quality control throughout production were enforced. Tight control enabled the manufacturer to turn out solid-propellant motor cases which consistently met proof stresses at 235,000 psi.[5] These cases, made of 4340 steel sheet and manufactured by the conventional roll-and-weld process, showed that improved regulation of materials and processes may provide a better solution than elimination of welding.

Weldability

The weldability aspects involving effects produced by the thermal cycle during welding are a second important consideration in the selection of base materials for weldments. The fact that many materials of seemingly identical nominal composition show differing tendencies toward crack development and embrittlement during welding has often been noted in the literature of the last two decades. Moreover, the search for a suitable "weldability" test for evaluating base metals has been a high priority research and development objective almost since the inception of structural welding. The extensive work that has been done in these areas indicates that there are existing gaps in knowledge concerning base metal controls required to avoid degradation of heat-affected zones resulting from the thermal cycles of welding. A wealth of evidence that weld heat-affected zones are intimately involved as critical regions of brittle behavior has been presented over a period of time. Nevertheless, the possible degradation that welding thermal cycles might produce is seldom accorded consideration as a factor governing base metal selection when structural fabrication is to be done by welding.

Heat-Affected Zone Cracking

In general, there are two different types of heat-affected zone cracking which are encountered in welding. These are cold-cracking and hot-cracking. Of the two, cold-cracking is probably the more insidious as it is difficult to detect and can occur immediately after welding or after a lapse of a considerable period of time, e.g., hours, days, or weeks. From the brittle fracture standpoint, neither type is tolerable.

Heat-affected zone hot-cracking has not generally been considered a problem of great magnitude. However, there is indication in some recent research that such cracking may be more important than has previously been recognized. For example, investigations have shown that microscopic size hot-cracks are one of the defects most often found in high-strength and ultrahigh strength weldments.[6-9] Considerable research was done to study the nature of weld hot-cracking in high-strength steels such as AISI 4340. A recent addition to this work has shown that heat-affected zone cracking in high silicon steel weldments may be likely because of apparent grain boundary liquation and also that such micro-defects can and do cause low-load failures.[10] It has also been reported[11] that hot-cracking has been found in some of the high-strength constructional steels having yield strengths of 80,000 psi and higher. Moreover, it appears that this type of cracking can be related to heat-to-heat as well as plate-to-plate compositional variations in the base materials.

Because hot-cracking has previously been considered to be more of a weld metal than a base metal problem there will be more said about the subject in the section on cracking. However, hot-cracking, when it does occur in the heat-affected zone, is thought to be primarily important because of the influence it may have on the propagation of cold cracks. Tiny hot cracks in the heat-affected zones may act as initiation points for cold cracks. This makes the steel more susceptible to cold-cracking than it would be if the hot cracks were not present.

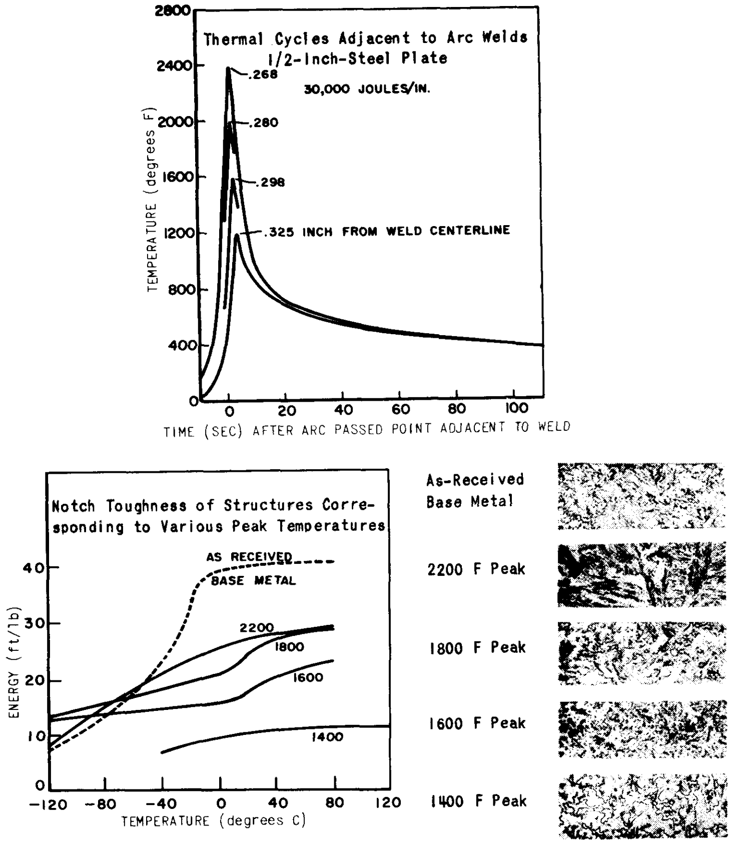
An excellent review of the cold-cracking problem was included as part of a recent study[12] by Rensselaer Polytechnic Institute on some government-sponsored research. Although the principal objective of this work was to establish a test for cold-cracking sensitivity, a literature survey was included in the published report. This report, containing some 57 references, would serve as a rewarding starting point for anyone seeking a bibliography on the current status of cold-cracking technology for alloy steels.

A review of the literature up to 1939 was presented by Spraragen and Claussen.[13] Since then salient progress has been made in research seeking a mechanism to explain the cold-cracking phenomena. By 1945 the three primary requirements for cold-cracking had been recognized and studied in some detail. These requirements were: the presence of martensite in the heat-affected zone, the introduction of hydrogen into the heat-affected zone, and the presence of restraint stresses in the welded structures. Later, control of carbide distribution was pointed out as a means of promoting resistance to cold-cracking. While voluminous literature describing outstanding research on detailed mechanisms has been presented in the interim, these four factors still appear to be the governing elements over which proper controls are required for prevention of cold-cracking in the weld heat-affected zones of alloy steels.

With regard to control of welding operations, it has been pointed out[14] that the beneficial effects of preheating and postheating which are used extensively as the prime procedure to avoid cold-cracking could be explained. Preheating increases the time available for hydrogen diffusion (and evolution) and postheating transforms retained austenite to higher temperature transformation products (bainite) from which hydrogen can diffuse more readily. An additional benefit is that preheating and/or postheating imposes a preventive control over the formation of the most undesirable hard and brittle transformation products, as well as imposing some degree of low-temperature tempering of autogenetic transformation products as an inherent part of the operation. A secondary benefit of postheat may be in reducing the stress gradient created during the critical part of the weld cooling cycle.

Heat-Affected Zone Embrittlement

The heat-affected zone is usually defined as that portion of the base plate adjacent to the weld metal which has not been melted but whose mechanical properties or microstructure have been altered by the heat of welding. In heat-treatable materials this zone can be divided into two parts. The first is that part which has been heated to temperatures below the lower critical. The second is that part which has been raised to temperatures between the lower critical and the melting point. The first zone has seldom been regarded as having much importance to the brittle fracture problem. There may be some exceptions to this rule if strain-aging or temper embrittlement entered the picture but to date there has not been enough work done to determine whether these phenomena have significant implications. The second zone is where most of the problems connected with poor heat-affected zone behavior have been shown to occur. In addition, embrittlement can occur in this region. Figure 2 shows one case that is indicative of the embrittlement that



Wtn. 639-15,494

Figure 2. HEAT-AFFECTED ZONE EMBRITTLEMENT

can be produced by the thermal cycles of welding. In this case, simulated thermal cycles in specimens of a 0.30C Mn-Mo type armor steel resulted in maximum embrittlement in the 1400 F peak temperature region.[15]

Similar results have been shown for other low-alloy high-strength ferrous materials.[16] Studies at Rensselaer Polytechnic Institute using their simulated specimen technique have shown that satisfactory yield strength and low-temperature notch toughness for subzero temperature service are exhibited by many low-alloy steels in plate form prior to welding fabrication. However, exposure to welding thermal cycles may so alter the microstructure that the resultant properties of the weld heat-affected zone are markedly impaired. Thus it is apparent that weldability, as well as strength and notch toughness, must be considered in the design of basic structural welding materials if the necessity for post-welding heat treatment is to be eliminated.

WELD METAL FACTORS AFFECTING MECHANICAL BEHAVIOR

Notch Toughness

It has been pointed out previously that the behavior of the base plate has been of singular importance in a majority of the brittle fractures of weldments for which post-failure analyses have been reported. Mild steel base materials quite often had fracture propagation properties which were not as good as those of the weld metals that were used. The fracture, no matter where it initiated, tended to run either into the base plate or into the heat-affected zone of the weld. It rarely ran in the weld metal itself. In some cases the base plate fracture behavior was poor even at temperatures as high as 80 F.[11]

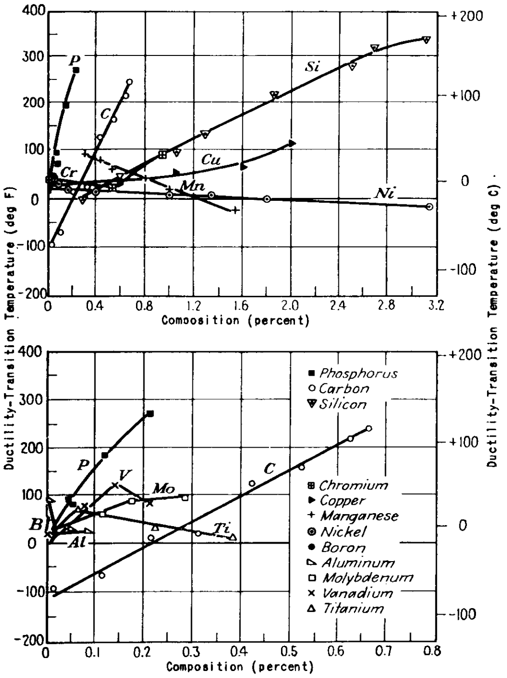
In a report covering a review of welded ship failures[17] it was observed that the influence of welding on notch toughness was not clear. The toughness of the weld metal as judged by impact tests was found generally to be better than that of the base metal. Some tests indicate that welding causes a loss of ductility of the base plate next to the weld. Other tests have shown that the notch toughness of welded specimens is much less than that of comparable unwelded specimens. This review goes on to point out that in actual ship failure, cracks which started in defective welds (welded butts for example) usually propagated in the plate. It might be mentioned that the plates which the fracture entered after having originated in a defective weld were of low notch toughness. Cracks did not even follow the plate next to the weld except in a few cases, and then only for a short distance. When cracking did follow the weld joints, it was where weld quality was poor. Similar observations were made in several cases where damage resulted from explosion. Such results suggest that the influence of welding may be different for crack initiation than for crack propagation. It also suggests that the mechanism of fracture in a welded joint may have directional properties.

High-strength structural materials do not necessarily behave the same as the lower strength materials. Quite often high-strength weldments will fail through or in the region immediately adjacent to the weld. Actually, in very brittle materials multidirectional failures are quite common (see, for example, Monograph MS-48, Page IV-15). In ductile failures the direction and location of fracture can usually be related to load patterns, and failure location is oriented in the direction dictated by highest stress. In brittle failure it is difficult to pinpoint just what predetermines fracture orientation. In some cases it may be decided by the location of the most highly notch-sensitive structures. The effects that residual stress patterns may produce still have not been fully determined. In any case the toughness of the weld metal could be a most important factor in deciding the location of initiation and direction for propagation of the fracture.

This, then, brings up the question of what determines the toughness of weld metal. Basically, weld metal properties are determined by composition and microstructure. In this respect weld metal does not differ greatly from any other form of metal. The same chemical elements and microstructures that are damaging to the basic metals are also damaging to the properties of weld metals. There are, however, additional considerations which must be contended with in welding. Some of these are discussed in the following paragraphs.

Fundamentally, a weld is a specialized sort of casting. One can think of a weld as a unique type of continuous casting being made in a chilled mold. Accordingly, the welding procedure, the melt (filler) material, and the nature and configuration of the mold (base) material are all factors affecting the final properties of the weld. Because the weld metal solidifies against the restraint imposed by rigid surroundings, shrinkage and residual stress factors are also active in affecting the final properties developed in the welds.

It is always dangerous to generalize in areas where a great deal more research is needed to establish fundamental information. Moreover, despite the fact that a large quantity of the literature which has been published on welding has been devoted to discussion of notch toughness, there is still much to be learned on the subject. About all that can be accomplished in a document of this kind is to present some guides on current concepts concerning a few of the factors that appear important.



19-066-1267/AMC-63

Figure 3. **EFFECT OF CHEMICAL COMPOSITION ON DUCTILITY-TRANSITION TEMPERATURE.** The curves are based on corrected values obtained by adjusting the experimental transition temperatures to constant values of carbon, manganese, and silicon, except when these were intentionally varied.

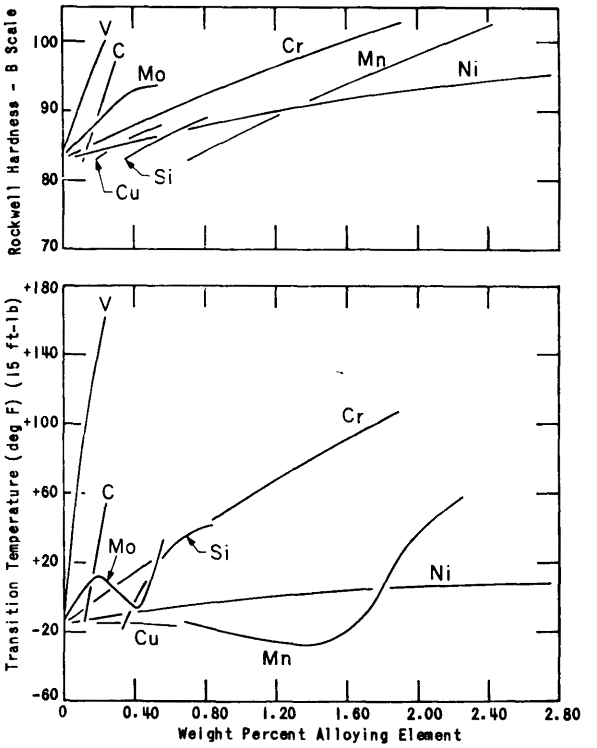
Reprinted from ASM Trans. v. 43, 1951. Courtesy of American Society of Metals.

As mentioned above, chemical composition affects toughness of both weld metal and base metal in a similar fashion. Accordingly, most of the information that has been developed on the basic materials will also be applicable to weld deposits. There have been numerous studies directed toward determining the effects of alloying elements on the toughness of steels. A review pertinent to the subject has been included in Chapter VI of MS-48. For the purposes of this article, one of the most systematic studies that has been made was that of Rinebolt and Harris,[18] who presented the data for pearlitic steels shown in Figure 3.[19] From this figure it may be seen that additions of carbon, phosphorus, and silicon greatly increased the ductility-transition temperature. Additions of molybdenum and copper moderately increased the transition temperature whereas those of manganese and nickel lowered it. The effects of other elements were more complex.

Additional investigation of the effects of energy input, restraint, and filler metal composition has been made by Dorshu and Stout at Lehigh University.[20] This report showed that lowering welding energy input, reducing restraint, and adding nickel and manganese were beneficial to weld metal notch toughness. They also studied weld metal deposited in grooved A201 steel plate, using both the inert-gas shielded consumable electrode and submerged-arc welding processes. The effects of alloying elements investigated during this study are shown in Figures 4 and 5.

Comparison of the effects of processes on toughness when depositing the same filler wire is given in Figure 6.[11] Reference 11 also contains additional data obtained from a review of literature on the effects of alloying elements on notch toughness in welds. An important factor not previously covered but which was emphasized in this report is the effect of oxygen as shown in Figure 7. This illustration shows that there can be a drastic increase in transition temperature at a very low oxygen content. Since all welds contain oxygen in varying amounts, it is reasonable to expect that a similar type of behavior would occur in weld metal.

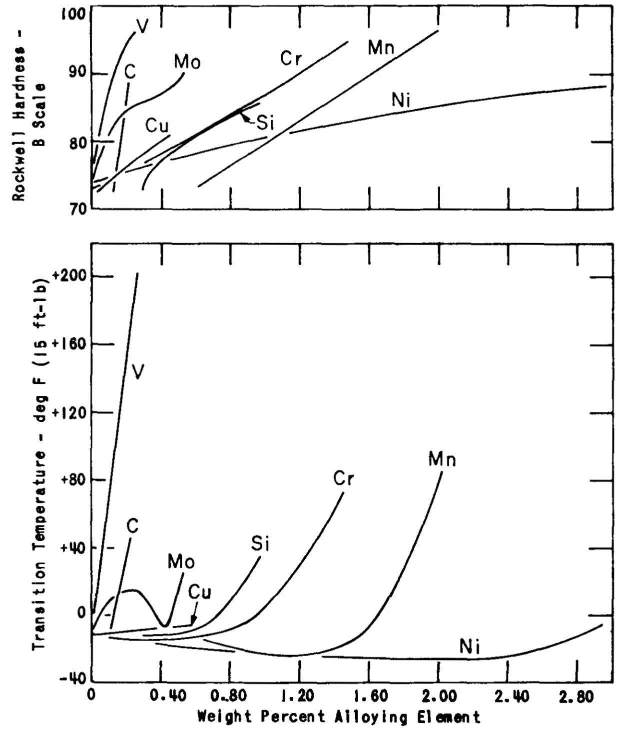
Westinghouse Research Laboratories, on a contract with the U. S. Navy, further substantiated this point.[21] They have also included nitrogen effects as being severely detrimental. One conclusion reached in their study was that the results provided almost completely convincing evidence that the key to achievement of strong tough welds is the problem of oxygen and nitrogen elimination. Furthermore, their research has pointed up other elements, such as antimony, hafnium, boron, phosphorus, and sulfur, even in minor amounts, as being detrimental. Vanadium, even in small amounts between 0.10 and 0.70 percent, resulted in brittle welds when tempered or stress-relieved.



19-066-1272/AMC-63

Figure 4. EFFECT OF ALLOY ADDITIONS ON NOTCH TOUGHNESS AND HARDNESS OF GAS-SHIELDED ARC WELD METAL

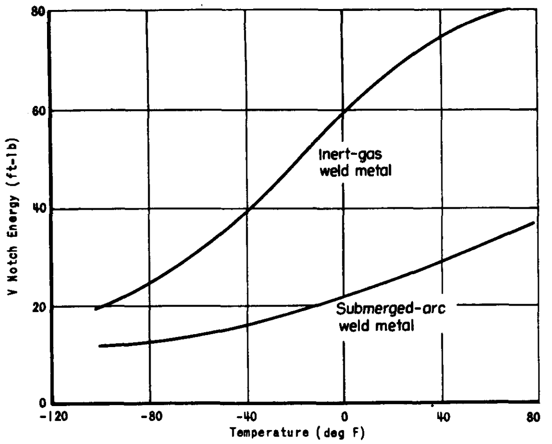
Reprinted from Welding Journal, v. 40, no. 3, 1961.
Courtesy of the AMERICAN WELDING SOCIETY.



19-066-1266/AMC-63

Figure 5. EFFECT OF ALLOY ADDITIONS ON NOTCH TOUGHNESS AND HARDNESS OF SUBMERGED ARC WELD METAL

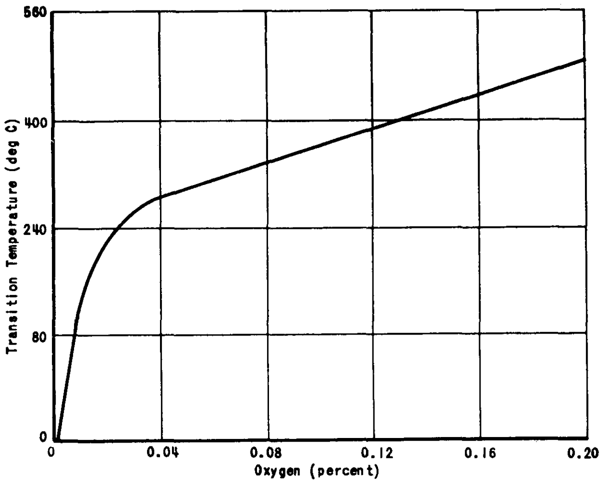
Reprinted from Welding Journal, v. 40, no. 3, 1961.
Courtesy of the AMERICAN WELDING SOCIETY.



19-066-1268/AMC-63

Figure 6. COMPARISON OF NOTCH TOUGHNESS OF SUBMERGED-ARC AND INERT-GAS-SHIELDED WELD METALS (using same filler wire, welding procedures, and commercial materials). Yield Strength of Weld Metals about 100,000 psi.

Reprinted from DMIC Report 172.



19-066-1269/AMC-63

Figure 7. EFFECT OF OXYGEN ON TRANSITION TEMPERATURE OF IRON-OXYGEN ALLOYS

Reprinted from DMIC Report 172

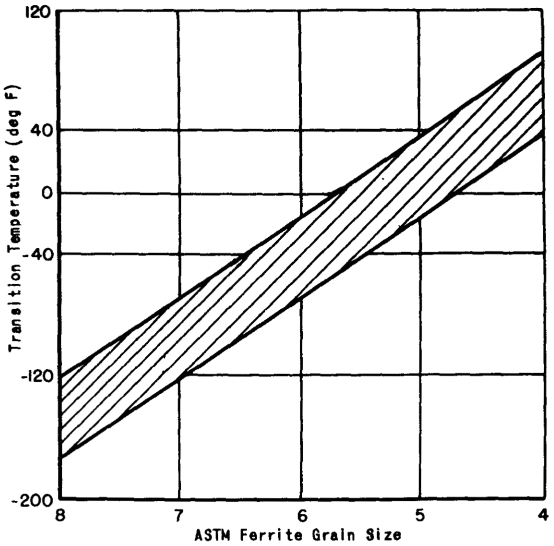
The Westinghouse researchers also stated that there has been a widespread and often-quoted opinion in the welding industry, that the type of brittleness being encountered results from the presence of low melting point eutectics. The data which they were reporting indicated that the observed brittleness probably resulted from the presence of excessive quantities of refractory oxides which are already solid while the bulk of the newly deposited weld metal is molten. Titanium, zirconium, columbium, and possibly aluminum were particularly damaging.

Hydrogen, in very small amounts, is of course detrimental. The effects of hydrogen on cold-cracking in weld metal are similar to those discussed previously in connection with heat-affected zone cracking. Furthermore, many other investigations have shown hydrogen to be detrimental to the ductility and toughness of weld metal deposits. In some cases aging has improved the mechanical properties, while in others, where fissuring has occurred, no amount of aging can remove the damage. Experience has shown that improved properties are obtained even in mild steel weld metal with the use of low hydrogren electrodes. Because of the detrimental effects on toughness, low hydrogen welding practices have become imperative for the fabrication of higher strength structural materials. In metal-arc welding, electrode variables associated with moisture content in the electrode coatings have been shown to be one of the most important factors related to heat-affected zone cracking.[22]

Besides composition there is little doubt that ferrite grain size can and does affect weld metal toughness. Figure 8[11] illustrates the effect of ferrite grain size on transition temperature for steel. Similar data for weld metal is difficult to find, but it is reasonable to assume that weld metal would produce similar results. While grain size is partially a function of composition, procedural factors are also a controlling parameter. As a general rule, procedures providing low heat inputs are usually favored for producing fine grain size and accordingly better weld metal notch toughness properties.

Cracking

Hot-cracking is another important potentiality that affects the toughness of weld metal and is also composition-related. Apblett and Pellini,[23] in a report discussing the factors which influence hot-cracking, stated that the development of hot cracks in welds results from the combined effects of metallurgical and mechanical factors. Metallurgical factors relate to conditions of strain developed in the weld metal during solidification due to differential cooling at various weld and near-weld positions. It was demonstrated in their report that certain high-temperature alloys are inherently susceptible to hot-cracking because of unfavorable conditions of solidification. Such alloys require close control of welding procedures to prevent hot-cracking.



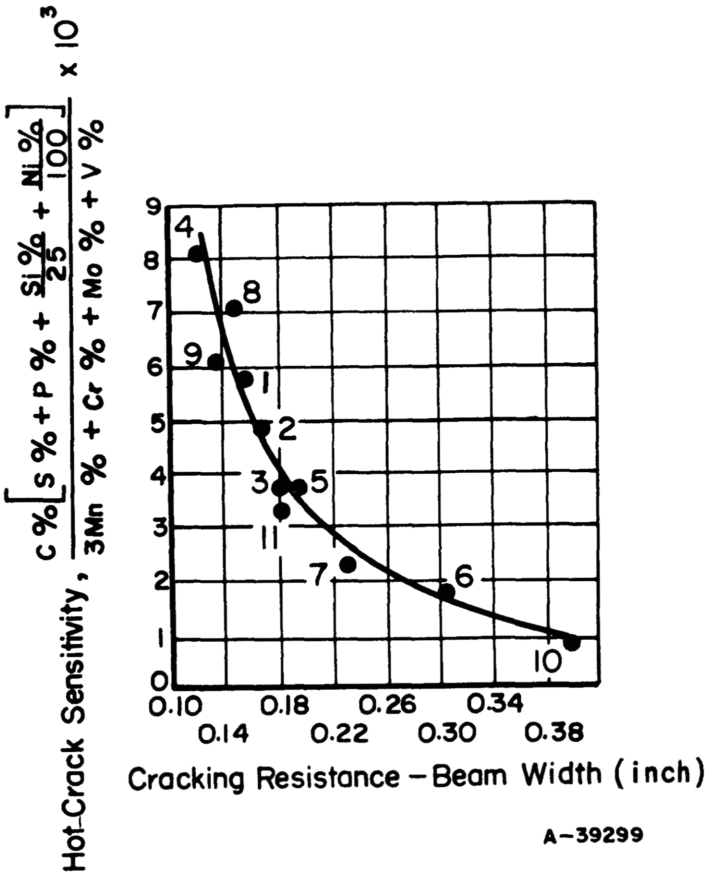
19-066-1270/AMC-63

Figure 8. EFFECT OF FERRITE GRAIN SIZE ON TRANSITION TEMPERATURE OF A NUMBER OF LOW CARBON (0.01-0.02 PERCENT) STEELS CONTAINING VARIOUS AMOUNTS OF OTHER ALLOY ELEMENTS

Reprinted from DMIC Report 172

DMIC Report 172[11] also contains a rather extensive review on the subject of hot-cracking. The authors describe two theories of explanation for the hot-cracking phenomenon. One theory is based upon the liquation concept. This theory involves the existence of low melting point eutectics or intermetallic compounds in the grain boundary which finally form shrinkage voids that eventually lead to cracking. The other theory for hot-cracking is based on the hypothesis that a brittle intergranular solid phase exists at high temperatures. The assumption here is that grain boundaries can be easily separated by low strains when stresses are imposed during subsequent cooling. Both theories may apply in different cases depending on the type of material involved. The brittle phase theory appears to be of particular importance in explaining hot ductility at about 1800 F in the chromium-nickel types of austenitic steels.

Chemical composition appears to be the controlling factor involved as far as hot-cracking is concerned. Figure 9, which appeared in the DMIC report,[11] presents an experimental formula which has been developed and which relates hot-cracking sensitivity directly to weld metal composition. Though empirical, this formula at least gives some indication of the elements which exert important influences on notch toughness because of hot-cracking susceptibility.



Legend

Steel Compositions

No.	Composition (%)								
	C	Mn	Si	S	P	Ni	Cr	Mo	V
1	0.33	0.51	0.16	0.015	0.023	0.15	0.91	0.20	--
2	0.31	0.55	0.36	0.007	0.020	0.12	0.86	0.19	--
3	0.28	0.55	0.28	0.008	0.018	0.12	0.95	0.25	--
4	0.31	0.42	0.22	0.017	0.034	0.17	0.85	0.24	--
5	0.36	0.60	0.16	0.007	0.018	0.30	1.17	0.285	--
6	0.24	0.48	0.20	0.013	0.014	0.16	3.04	0.53	--
7	0.38	0.63	0.33	0.008	0.013	0.19	3.13	0.87	0.24
8	0.35	1.57	1.55	0.011	0.018	1.80	0.11	0.34	0.21
9	0.32	0.64	0.18	0.011	0.020	1.90	0.85	0.22	--
10	0.21	0.35	0.23	0.014	0.025	0.26	12.92	--	--
11	0.37	0.41	1.10	0.012	0.014	0.22	4.9	1.50	0.54

19-066-1271/AMC-63

Figure 9. EFFECT OF STEEL COMPOSITION ON HOT-CRACK RESISTANCE

Reprinted from DMIC Report 172

Microstructure

Associated with all the preceding factors which affect notch toughness is the importance of microstructure. In many respects this is probably the most important of all the factors associated with brittle fracture in weld metals. It would not be feasible in an article of this sort to delve into an extensive discussion of microstructure. Suffice it to say that the same metallurgical structures which are lacking in toughness in any form of metallic material lead to brittleness in weld metals also.

As indicated earlier in this section, weld metal bears some similarity to casting in a chilled mold. The heat flow effects are size- and procedural-dependent but in most cases the accelerated cooling is of significant magnitude. In many cases the quench effect is of the order of the rates of cooling obtained with a water quench. Because the heat flow in the weld zone is generally highly directional toward the adjacent cold metal, the weld develops distinctly columnar grains at right angles to the bond. The first crystals forming in a molten alloy may differ markedly in composition from the liquid, but as freezing proceeds, equilibrium requires that the crystals readjust their composition to that of the initial liquid alloy. However, liquid and solid phases may depart from one another in composition by a wide range while freezing is in progress. The adjustments in composition which then occur depend on diffusion. It can be appreciated that in the rapid cooling of weld metal, the requisite time for diffusion may not be available. Also, the distance over which diffusion must take place may require a relatively long time. It is normal then for weld metal to be heterogeneous in composition upon freezing. This condition is called segregation and results in a cored dendritic structure. In weld metal, the heterogeneity is microscopic and cannot be detected by chemical analysis of chips from a drilled sample.[19]

Because of the tendencies for segregation to occur, there can be planes of weakness in weld metal which may lead to premature failure. Also due to inhomogeneity, there can be areas which are more highly alloyed than is indicated by nominal composition and which on cooling produce hard and brittle structures in the as-cooled condition. Such structures are inherently prone to brittle fracture.

It is possible in many instances to obtain improvement in weld metal toughness by establishing proper welding procedures. Since the structures formed in welding have peculiarities related to unique characteristics of the operation, it follows that much can be done to regulate microstructures and therefore properties in a weld through process control. The ability of a weld metal to form a sound, serviceable joint is determined by the composition of the metal and the circumstances under which the metal solidifies and cools to room temperature. In the welding of a given material the properties and characteristics of the welds may be changed by using a different procedure and technique. Unfortunately, because of the complex process and physical metallurgy involved, no set rules can be given for procedures which will be beneficial in all cases. The proper procedures for one material might be highly embrittling in a different alloy. Hence, the services of a competent welding specialist are invaluable. By combining his knowledge and experience with some preproduction experimental work, the welding engineer can often devise procedures which will at least minimize brittle weld failures.

SUMMARY

When a welded structure fails, the weld is often assumed to be the "weak link" responsible for the failure. Post-failure analysis, however, may reveal that the failure was due to human error in design or materials engineering rather than to the mere fact that welding was involved.

It would be impractical in a review of this type to attempt to cover all of the innumerable chemical, metallurgical, and mechanical factors which influence brittle performance in weldments. Suffice it to say that engineers should be aware of the drastic consequences that can derive from inadequate toughness in weldments. If the subjects discussed here stimulate respect for the damage that can be done by poor structural design involving weldments, the intent of this document will have been accomplished.

A guide of common welding deficiencies and recommended remedial action is appended.

APPENDIX

A BRIEF GUIDE TO SOME COMMON WELDING DIFFICULTIES AND REMEDIES FOR THEM[19]

TABLE I

CAUSES	REMEDIES
Low Weld-Metal Ductility and Notch Toughness	
1. Too rapid cooling	1. Increase heat input; preheat; postheat
2. Improper electrode	2. Change to an electrode which will deposit metal having greater ductility and notch toughness
3. Excessive carbon and alloy pickup from base metal	3. Decrease penetration by lowering the current or the travel speed; change to a low penetration electrode
Low Base-Metal Ductility and Notch Toughness	
1. Too rapid cooling	1. Increase heat input; preheat; postheat
2. High hardenability of base metal	2. Increase heat input; preheat; postheat
3. Strain aging in base metal	3. Heat treat completed weldment

TABLE II

CAUSES	REMEDIES
Weld Metal Cracking	
1. High rigidity of joint	2. Preheat; use peening; change welding sequence by back-stepping or block welding; increase cross section of bead
2. Unsound welds	2. See Porosity and Inclusions
3. Defective electrodes (high or low moisture in coating, poor core wire)	3. Change electrode; control moisture by proper storage
4. Poor fit-up	4. Reduce root gap, butter edges
5. Small or shallow bead	5. Increase cross section of bead; change electrode type
6. Excessive carbon or alloy pickup from base metal	6. Reduce penetration by lower current and travel speed; change to low-penetration electrode
7. Angular distortion, causing tension at weld root	7. Balance welding on both sides; use peening
8. Excessive sulfur in base metal	8. Use EXX15-16 electrodes

TABLE II (Cont)

CAUSES	REMEDIES
Base Metal Cracking	
1. Hydrogen in welding atmosphere	1. Use EXX15-16 electrodes; submerged-arc or inert-gas-shielded-arc processes; preheat
2. High hardenability	2. Preheat; increase welding heat input; postheat without cooling after welding
Porosity	
1. Excessive hydrogen or oxygen in welding atmosphere	1. Change electrode or regulate gas-welding flame to avoid oxidation
2. High rate of weld freezing	2. Increase heat input; preheat
3. High-sulfur base metal	3. Use EXX15-16 electrodes
4. Oil, paint, or rust on steel	4. Clean joint surfaces
5. Improper arc length, current, or manipulation	5. Use longer arc (within recommended voltage range); control welding technique
6. Excessive moisture in electrode or joint	6. Use dry electrodes and dry materials
7. Heavy galvanized coatings	7. Use E6010 electrode
Inclusions	
1. Failure to remove slag from previous deposit	1. Clean surfaces and previous beads properly
2. Oxidizing welding atmosphere	2. Regulate flame in gas welding to neutral
3. Improper joint design	3. Observe proper arc length and manipulation

Reprinted from **WELDABILITY OF STEELS**,
Courtesy of Welding Research Council, 1953.

LITERATURE CITED

1. WILLIAMS, M. L., and ELLINGER, G. A. *Investigation of Structural Failures of Welded Ships.* The Welding Journal, v. 32, no. 10, October 1953, p. 498S-527S.

2. FELBECK, D. K. *Today's Trend in Ship Research.* The Welding Journal, v. 37, no. 6, June 1958, p. 265S-268S.

3. RANDALL, M. D., MONROE, R. E., and MARTIN, D. C. *New Developments in Welded Fabrication of Large Solid Fueled Rocket Motor Cases.* Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, DMIC Report 173, August 1962.

4. SHANK, M. E., SPAETH, C. E., COOKE, J. W., and COYNE, N. E. *Solid Fuel Rocket Chambers for Operation at 240,000 psi and Above.* Metal Progress, v. 76, November 1959, p. 74-81.

5. HEISE, R. E. *Better Cases for Missiles, III-Advanced Fabrication Methods.* Metal Progress, v. 80, no. 1, July 1961, p. 105-107.

6. SOPHER, R. P., JACOBS, A. J., and RIEPPEL, P. J. *Investigation of Weld Metal Cracking in High-Strength Steel Weld Metals.* The Welding Journal, v. 34, no. 11, November 1955, p. 544S-552S.

7. SOPHER, R. P. *Effects of Chemical Composition on Cracking Resistance of High-Strength Steel Weld Metals.* The Welding Journal, v. 37, no. 11, November 1958, p. 481S-492S.

8. WILKINSON, F. J., COTTRELL, C. L. M., and HUXLEY, N. V. *Calculating Hot Cracking Resistance of High Tensile Alloy Steel.* British Welding Journal, v. 5, no. 12, December 1958, p. 557-562.

9. MISHLER, H. W., MUNROE, R. E., and RIEPPEL, P. J. *Studies of Hot Cracking in High-Strength Weld Metals.* The Welding Journal, v. 40, no. 1, January 1961, p. 1S-7S.

10. RANDALL, M. D., MONROE, R. E., and RIEPPEL, P. J. *Causes of Microcracking and Microporosity in Ultrahigh-Strength Steel Weld Metal.* The Welding Journal, v. 41, no. 5, May 1962, p. 193S-206S.

11. DEFENSE METALS INFORMATION CENTER. *Background for the Development of Materials to be Used in High-Strength Steel Structural Weldments.* Battelle Memorial Institute, Columbus, Ohio, DMIC Report 172, 31 July 1962.

12. NIPPES, E. F., SAVAGE, W. F., and LEVINE, E. D. *Weld Heat-Affected Zone Cracking in Armor Steels.* Rensselaer Polytechnic Institute, Final Report, Contract DA-20-089-ORD-38859, May 1960.

13. SPRARAGEN, W., and CLAUSSEN, G. E. *Weldability-Base Metal Cracks.* The Welding Journal, v. 20, 1941, p. 201S.

14. HOYT, S. L., SIMS, C. E., and BANTA, H. M. *Metallurgical Factors of Under Bead Cracking.* Transactions, AIME, v. 162, 1945, p. 326.

15. HARTBOWER, C. E. *V-Notch Charpy Impact Testing Welded Joints.* Proceedings of the Third Sagamore Ordnance Materials Research Conference, Duke University, Durham, North Carolina, December 1956, p. 557-579.

16. NIPPES, E. F., and SIBLEY, C. R. *Impact Performance of Synthetically Reproduced Heat-Affected Zone Microstructures in T-1 Steel.* The Welding Journal, v. 35, no. 10, October 1956, p. 473S-480S.

17. ACKER, H. G. *Review of Welded Ship Failures.* Welding Research Council, New York, Bulletin Series No. 19, November 1954.

18. RINEBOLT, J. A., and HARRIS, W. J., JR. *Effect of Alloying Elements on Notch Toughness of Pearlitic Steels.* Transactions, ASM, v. 43, 1951, p. 1175-1214.

19. STOUT, R. D., and DOTY, W. D. *Weldability of Steels.* Welding Research Council, New York, 1953.

20. DORSHU, K. E., and STOUT, R. D. *Some Factors Affecting the Notch Toughness of Steel Weld Metal.* The Welding Journal, v. 40, no. 3, March 1961, p. 97S-105S.

21. HEUSCHKEL, J., et al. *Development of a Steel, Weld Metal and Welding Procedure Capable of Producing 150,000 psi. Yield Strength in Heavy Sections.* Westinghouse Research Report 925-1900-R4, October 1961.

22. HATCH, W. P., and POTEAT, L. E. *The Cruciform Test for Plate Cracking Susceptibility II.* U. S. Army Materials Research Agency, WAL 710/1081-1, March 1962, p. 12.

23. APBLETT, W. R., and PELLINI, W. S. *Factors Which Influence Weld Hot Cracking.* The Welding Journal, v. 33, no. 2, February 1954, p. 83S-90S.