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SOME FRACTURE PROBLEMS IN WELDED HIGH STRENGTH MEMBERS

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ABSTRACT

Because of the many modes of fracture that may develop, the strength of a weldment cannot be predicted on the basis of tensile strength of the metals joined. Better control of the processes and procedures are required at every stage of design, development and fabrication to avoid fractures in the "higher strength" metals. Weld metal must be developed and deposited with a high degree of purity, and must be free from slag inclusions, micro-cracks, and excessive rates of heat input. For each potential mode of failure quantitative information must be obtained on the significant material properties that measure the nearness to damage of the weld metal, the plate and the heat affected zones. The designer must foresee all environmental factors, and base his design stresses on realistic estimates of the fundamental resistance of these zones to each possible mode of failure.

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Introduction

There is widespread interest (and great potential problems) in the development of welded structures from metals having tensile strengths in the range 100,000 to 200,000 psi. These problems increase in severity somewhat in proportion to the tensile strength. Such alloy systems must provide great toughness as well as strength, a requirement which can be achieved only with weld metals having a high degree of purity. Carbon must be kept at relatively low levels. Neither nitrogen, oxygen nor hydrogen can be tolerated. Weldments must be free of defects such as slag inclusions, lack-of-fusion or micro-cracks from which large cracks can develop. The welds must be as good as the plate.

Two classes of structures must be considered: a) small, thin sections, easy to position and which may be built in ideal environmental conditions; and b) heavy massive components where positioning and good fit prove virtually impossible, and built in dirty, cluttered, and drafty exposures by less sophisticated people. Where possible, all primary joints should be fabricated with mechanized devices which incorporate adaptive controls to compensate for irregularities in fit-up and edge preparation. But a sizeable percentage of welds in difficult zones must be made manually.

This technical note is issued to outline some of the potential failure modes that may develop, and to emphasize the significant material properties and environmental factors that should be evaluated for assurance of a safe, reliable structure.

There are many aspects of the fracture toughness, fatigue strength, and stress-corrosion behavior of materials that must be given careful consideration and evaluated quantitatively for structural components utilizing metals of increased tensile strength. For weldments, the structure must be regarded as consisting of three materials, all three of which contain "flaws" of varying sizes and types; these are:

(a) The basic plate material

(b) The weld metal

(c) The heat effected zones.

In the discussion which follows all quantitative measures of toughness, resistance to cyclic or slow flaw growth, etc., must be evaluated for each of these three elements of the metal structure if safe and reliable structural performance is to be assured in service.

Fracture Toughness

Intensive research on fracture toughness characteristics of metals during the past ten years has developed new test procedures and methods of quantitative evaluation. Unfortunately, the usual design criteria of tensile strength, yield point, and elongation do not give realistic information from which to determine the resistance of the metal to slow or cyclic flaw growth nor to predict the resistance to rapid crack propagation. In developing higher strength metals for weldments, it is essential to determine the basic parameters from fracture mechanics (K_{Ic} and K_{Iscc}) which characterize the resistance to rapid and to slow (time dependent) crack propagation in terms of flaw depth and nominal stress. These parameters which evolved from the field of fracture mechanics are applicable primarily to conditions of plane strain, and are widely in use for assuring that small flaws in thick sections will not cause fracture for the operating stress and particular environmental conditions. However, there remains a gap in our ability to predict the conditions necessary for resistance to rapid fracture in the higher toughness materials under conditions of plane stress.

The design parameters for resistance to catastrophic rupture from flaws of specific size can be readily predicted for conditions below and in the region of the nil ductility temperature by means of fracture mechanics. At higher temperatures, where somewhat increased toughness is available, there is substantial difference in the resistance to sudden shear (or tearing) rupture between steels of the same tensile properties. That is, the "shelf energy" in impact testing may readily vary by factors of two-to-one for different metals of the same tensile strength. W. S. Pellini* in his recent article has

*See references appended to this report

emphasized the metal cleanliness and melting practice in producing the steel as an important variable. That is, steels produced by vacuum induction melting plus vacuum arc remelting can be produced with low void site density to develop higher levels of plane stress fracture toughness. The increased costs of high-quality processing may be technologically essential to retain adequate toughness at high tensile strength levels. Similarly, retention of fracture toughness characteristics in welds, and in heat affected zones to match the plate properties becomes metallurgically more difficult with increase in strength level.

The dynamic tear tests, developed by Pellini, should certainly be given strong consideration as a performance index in evaluating steels and weld zones for optimum resistance in service conditions that are above nil-ductility temperatures. The attached Figs. 32 and 33, from the Pellini article, will illustrate the wide variability in toughness of steels in the range of 100 to 200 psi tensile strength.

In a general way for steels of increased tensile strength, the values of K_{Ic} and the ratios of K_{Ic}/σ_y will decrease. The designer, however, wishes to increase the design stress in some proportion to the increase of tensile strength. Thus, the tolerance for a given size flaw may be greatly decreased as the tensile strength is raised, and may result in a catastrophic fracture because of the increase in design stress. From the fracture mechanic's viewpoint, the tolerance on size of existing flaw that can be resisted decreases as $(K_{Ic})^2$. Hence, if the K_{Ic} for the higher strength steel is decreased to 80 percent of that for the lower strength steel, the depth of critical flaw for catastrophic fracture at a given stress would be decreased to 64 percent of that in the lower tensile metal. This, in spite of the fact that the designer then would try to operate the component at a higher nominal stress level based upon the increase in tensile strength. For very high strength metals the minute flaws that cannot readily be detected by ultrasonic or radiographic inspection can represent a critical flaw size that cannot be tolerated by the metal under the design stress condition. Only through improved melting practices, better methods of welding control, careful attention to heat cycles, and close attention to quality control and inspection methods can premature fractures be avoided in high tensile strength steels.

Fatigue Properties

As a general rule most engineers expect the fatigue strength to be increased in proportion to the tensile strength. This is primarily based on data from carefully polished, rotating beam, laboratory samples. For as-rolled, welded plate, one frequently finds that doubling the tensile strength may result in little or no increase in fatigue strength under conditions of reversed cyclic loading. Furthermore, if the fatigue life is limited to a "low cycle" life from periodic heavy loads in service, the higher strength metal may fail prematurely. Under cyclic plastic strain conditions in peak stress zones, the ductility is often more important than the tensile strength. Furthermore, at higher tensile levels the welds and plate in the structure frequently develop higher levels of residual stress from forming and welding. These inherent stresses may approach values close to the yield point. Thus we are confronted with probability that any advantage of higher "strength" may be offset by higher residual stresses in critical zones. Rough as-rolled surfaces, heat affected zones, and surface decarburization, together with the unavoidable presence of small flaws (or even micro-cracks) in and around welds can well account for lack of improvement in fatigue preoperties from the "higher strength" steels in weldments.

Corrosion

It is well known that as the tensile strength of a steel is raised it becomes more susceptible to stress-corrosion cracking in adverse environments; sometimes these may be as ordinary as moist air or water. This sensitivity may well be due solely to the fact that the nominal stresses have been increased to intensify or stimulate the interaction of local stress and environment. Great caution needs to be exercised, therefore, in anticipating residual stresses plus the selection of a design stress level that will not combine to develop time-dependent stress-cracking in the particular environment anticipated for the service condition.

Sensitivity to hydrogen embrittlement also is accentuated by tensile strength; the mechanism of embrittlement may be similar to that which develops stress-corrosion cracking. Processing operations and environmental conditions of service need to be studied with care to avoid hydrogen embrittlement. In addition, however, the processing of steels to higher levels should be carefully controlled to eliminate the type of small defects that have been given various names, such as "flakes," "shatter cracks," and "fish eyes." These result from hydrogen evolution during the cooling of steel from high temperature, and consists of small voids or interior flaws that could develop fatigue nuclei or result in catastrophic fracture. In general, these occur primarily in thicker sections from hydrogen absorbed while in the molten state.

Under conditions of cyclic loading, mild corrosive agents (including distilled water) result in an interaction (or mutual stimulation) between corrosive pitting and cyclic crack propagation. Irrespective of the steel involved, the corrosion fatigue strength is well below values that might be anticipated by thinking of a corrosive attack leaving pits that would reduce the fatigue strength from the geometric discontinuity. Practically all steels will have corrosion fatigue strengths in the range from, say, 8000 to 15,000 psi reversed stress. Increasing the tensile strength only makes the metal more susceptible, particularly since one is operating at higher nominal stresses which furnish more energy for stimulation of corrosion and cyclic crack propagation.

It is not known whether the higher strength steels that may be developed are susceptible to strain aging. This factor should be given careful consideration. Some of the low strength steels will age with time after cold working operations, such as bending, shearing, swaging, etc. Mild heating accelerates this aging. The end result is an increased tensile strength, accompanied by embrittlement, that may make a normally ductile metal behave in a frangible fashion to support catastrophic fracture with no evidence of ductility. It would be important to be assured that no such strain aging would occur in a weldment of higher strength metal.

General Considerations

The severe heat input and cooling rates involved in welding will alter the gross mechanical properties of the plate in local zones, and frequently result in complex triaxial residual stresses. The weld metal itself forms a crude casting which has some porosity and which may develop micro- or macro-cracks; some cracks may even occur many days or weeks later upon aging. The metallurgical changes in local zones of dissimilar material, the residual stresses, and possible depletion of ductility are all unfavorable structural characteristics inherent in welding.

Cold forming and cutting operations on steel plate develop cold-worked zones that may be susceptible to strain aging. An accelerated aging will occur in these steels in zones near the welds because of the heat supplied by the welding operation.

In view of all these influencing factors and because of the various types of failure that may occur, it is imperative that design stresses be based upon the significant quantity that measures the nearness to damage of the material in the mode of failure most probable. For example, the attached Table I is a preliminary attempt to list methods of evaluating the significant mechanical resistance for the various modes of failure to which the component may be susceptible (4). The last column of Table I needs to be expanded with better test methods for evaluation. It is important that design be based not on tensile strengths, but upon realistic values of the resistance of critical zones (with typical flaws) in and surrounding the weld.

The importance of foreseeing the possibility of every mode of failure is well illustrated by the collapse of the Point Pleasant Bridge (2). After forty years of service, a minute stress-corrosion crack (surface crack of 1/8 in. radius) in a large thick eye-bar was a critical flaw that resulted in sudden, catastrophic fracture. This eye-bar was heat treated to a yield strength of 80,000 psi and a tensile strength of 120,000 psi. No one had suspected that the material (and hence the structure) was susceptible to this type of failure.

The difficulty of fabricating high-strength weldments is well illustrated by the failure of a 260 in. diameter motor case (3). Even though the vessel was subjected to all of the best-developed methods of nondestructive testing, small flaws of critical size existed in welds that caused catastrophic failure at 56% of the desired proof pressure. These defects were generated by stresses set up by multi-pass TIG repair welds. Unfortunately, high heat input during submerged arc welding created grain coarsening and thermal embrittlement. This region was susceptible to cracking under stresses generated by heat cycles in repair welding.

For high strength weldments, a substantial portion of the welding may require repair. Thus, the mechanical properties in regions of repair welding need careful evaluation before production procedures are adopted. Small flaws, not detectable upon initial inspection, may grow under subsequent aging or be propagated by subsequent stressing until they reach critical size for catastrophic failure of the component.

Further Studies Needed

In general, for all three zones of interest (plate, weld, heat affected zones) and for components with fillet or butt welds, the following quantities should be evaluated before setting design stresses:

(a) Toughness characteristics in terms of K_{Ic} for surface flaws or for imbedded flaws, and dynamic tear test energy absorption; acquire data for the range of temperatures of operation intended.

(b) Stress corrosion cracking (or slow flaw growth) resistance for expected environment, dosage and temperatures. Typical K_{Iscc} values are needed for simulated service conditions. Tolerances for safe design stress levels need to be established for members having flaws of the size expected in normal production (or which are not readily detected by NDT).

(c) Fatigue strength characteristics for ordinary temperatures and dry environments in both low and high cycle conditions of loading. Directions of loading should include principal stresses both parallel and perpendicular to weld zones, and studies should be made of specific design details in which loads are transferred through a fillet weld as well as for full penetration butt welds. Influence of weld bead terminations in the loadpath, lack of full penetration, presence of porosity and microcracks, arc strikes, weld spatter, etc., all need careful quantitative evaluation.

(d) Fatigue strength characteristics for moist and liquid environments (such as ocean water) for developing safe design stress levels for foreseeable adverse environments. The same variables of geometry, potential flaws and loading as these under (c) should be evaluated.

(e) Residual stresses persisting in weld and surrounding plate after final processing operations. Evaluate susceptibility to stress-corrosion cracking or brittle fracture from the unfavorable residual stresses superposed on the stresses due to design loadings.

(f) Strain aging characteristics of the weld and basic plate metal following cold forming and welding. Local cold worked zones for many metals become embrittled from mild reheating after cold working. Values of K_{Ic} for the zones of plate, weld and heat affected zones are needed to measure the quantitative loss of toughness that may result with aging after cold work.

(g) Effect of "start" and "stop" pools of weld metal on each of the above structural strength characteristics.

(h) Influence of specific methods of weld repair procedures on each of the above structural strength characteristics. The propensity for adverse metallographic structure or the development of various types and sizes of flaws by repair welding can be controlling factors for several modes of failure.

The thickness of plate being welded must be given careful consideration in all of the above studies. Differences in rate of heat input, cooling rates, number of weld passes, and development of plane strain vs. plane stress conditions can have significant effect.

The many difficulties and unknowns outlined above make the problem of developing reliable high strength weldments rather discouraging. It is evident that better control of processes and procedures will be required at every stage of design, development, and fabrication. However, with employment of the latest technology in fatigue and fracture mechanics, development of adequate materials property data, and careful fabrication and inspection techniques, the problem is not insurmountable. The designer must foresee all possible environmental factors, and avoid all unnecessary geometrical stress-raisers in evolving a safe and reliable structure based upon realistic estimates of the fundamental material behavior.

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TABLE I.

RELATION OF FAILURE TO OPERATING CONDITIONS AND MECHANICAL PROPERTIES OF THE MATERIAL

MODE OF FAILURE	LOADING MODE			STRESS TYPE			OPERATING TEMPERATURE			MATERIAL TYPE		SIGNIFICANT MECHANICAL RESISTANCE OF THE MATERIAL MEASURED BY:
	Static	Repeated	Impact	Tension	Compression	Shear	Low	Room Temp.	High	Brittle	Ductile	
Brittle Fracture	X	X	X	X			X	X		X	X	Charpy "V"-notch transition temperature. Notch toughness. K_{IC} toughness measurements.
Ductile Fracture	X			X		X		X	X		X	Tensile strength. Shearing yield strength.
Fatigue (millions of cycles)		X		X		X	X	X	X	X	X	Fatigue strength for expected life, with typical stress raisers present.
Low Cycle Fatigue		X		X		X	X	X	X	X	X	Static ductility available and the peak cyclic plastic strain expected at stress raisers during prescribed life.
Corrosion Fatigue		X		X		X		X	X	X	X	*Corrosion fatigue strength for the metal and contaminant and for similar time.
Buckling	X		X		X		X	X	X	X	X	Modulus of elasticity and compressive yield strength.
Gross Yielding	X			X	X	X	X	X	X		X	Yield strength.
Creep	X			X	X	X			X	X	X	*Creep rate or sustained stress-rupture strength for the temperature and expected life.
Caustic or Hydrogen Embrittlement	X			X				X	X	X	X	*Stability under simultaneous stress and H_2 or other chemical environment.
Stress Corrosion Cracking	X			X		X		X	X	X	X	*Residual or imposed stress and corrosion resistance to the environment. K_{1scc} measurements.

* Items strongly dependent upon elapsed time.

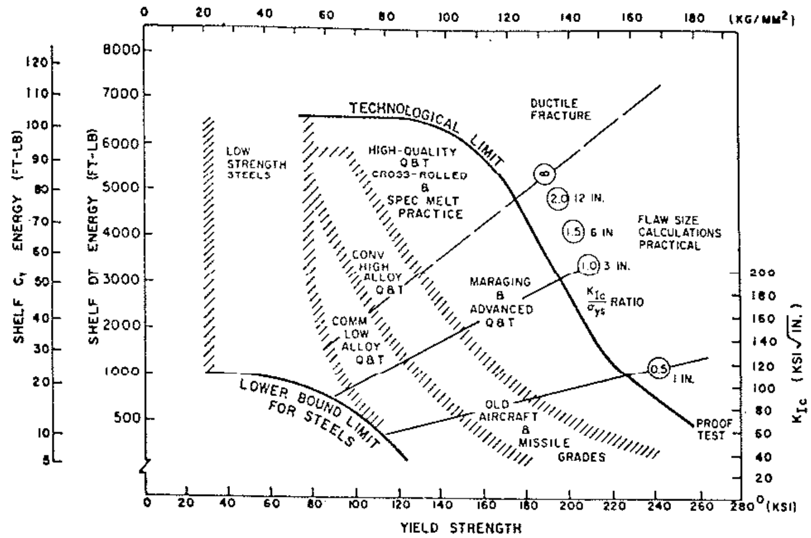

Fig. 32—Metallurgical zoning of the RAD which defines the general effects of melting and processing factors on the strength transition. The three corridors of strength transition relate to metallurgical quality (void site density) which controls microfracture processes and, thereby, the macroscopic fracture toughness of the metal. The locations of generic alloy steel types are indicated by the notations

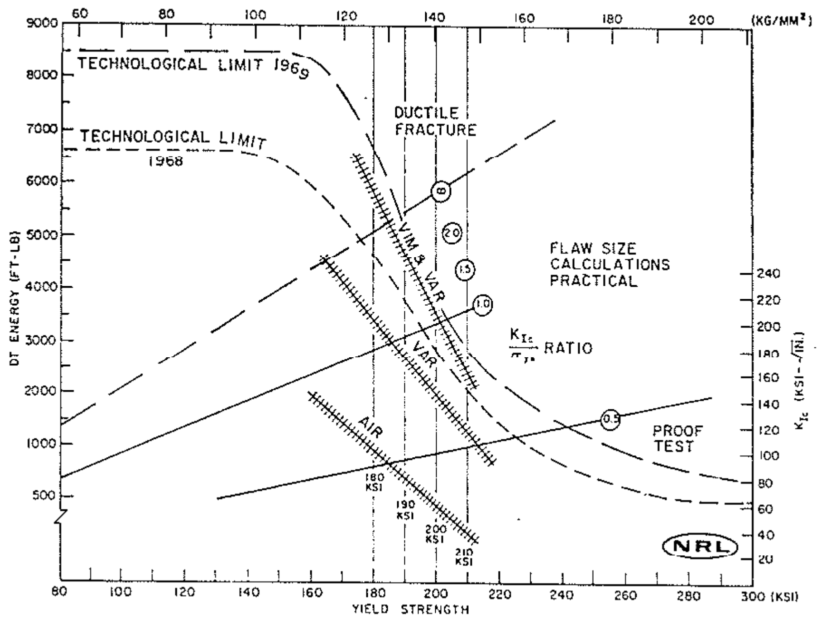

Fig. 33—Metallurgical zoning of the RAD which defines the effects of specific melting practices. These include air melting under slags (Air), vacuum induction melting (VIM) and vacuum arc remelting (VAR); a combination of these is indicated by the VIM-VAR notation. The extension of the Technological Limit curve to the 1969 position results from the use of advanced VIM-VAR melting practices at large production scale

*From Pellini, W.S."Principles of Fracture-Safe Design, "Welding Research (Supplement), March, 1971, pp. 91s:-109s; & April, 1971, pp. 147s-162s.