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CHARACTERIZATION OF WELDED HP 9-4-30 STEEL FOR THE ADVANCED SOLID ROCKET MOTOR

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INTRODUCTION

Solid rocket motor case materials must be high-strength, high-toughness, weldable alloys. The Advanced Solid Rocket Motor (ASRM) cases currently being developed will be made from a 9Ni-4Co quench and temper steel called HP 9-4-30. These ultra high-strength steels must be carefully processed to give a very clean material and a fine grained microstructure upon treat treatment. This insures excellent ductility and toughness. The HP 9-4-30 steels are vacuum arc remelted and carbon deoxidized to give the cleanliness required. The typical heat treatment consists of: (1) normalizing at 1650 ^{o}F, (2) austenitizing at 1550 ^{o}F for 1 hour and quenching in oil followed by cooling to -100 ^{o}F for 2 hours, and (3) double tempering at 900-1000 ^{o}F for 2 hours. Typical properties are shown in Table I with some ASRM tentative requirements.

Table I

	HP 9-4-30	ASRM
UTS (ksi)	227	200
YS (ksi)	206	225
Elongation (%)	23	17
RA (%)	54	-
K_{IC} (ksi (in.)$^{1/2}$)	120	-

The ASRM case material will be formed into rings of the required thickness and diameter, and then welded together to form the case segments. Welding is the desired joining technique because it results in a lower weight than other joining techniques. Consequently, weldability of the HP 9-4-30 is very important and, as in most cases, the joint becomes the critical link in the structure. For this reason the mechanical and corrosion properties of the weld region material must be studied fully.

This research effort, carried out at the Metallurgy Research Branch (EH23) at the Marshall Space Flight Center, consisted of studying the microstructure of the fusion zone (FZ) and heat affected zone (HAZ) of welded HP 9-4-30. The microstructures were then related to the mechanical properties of the weld metal where possible. In addition, the relationship of certain weld joint design and weld process parameters was examined and related to the mechanical properties.

DISCUSSION

The mechanical properties of a metal are closely related to the microstructure. A study of the microstructure and related mechanical properties often identifies failure mechanisms and the means to modify the microstructure and achieve the desired properties. The welding process produces significant microstructural changes in the weld FZ and HAZ which then influence the properties. Upon welding, quench and temper steels like HP 9-4-30 may undergo significant changes such as: (1) a distinctive solidification substructure in the FZ, (2) grain growth and/or refinement in the FZ and HAZ, (3) micro and macrosegregation, and (4) retained austenite. The techniques used to study the microstructural/property relationships were tensile testing, light microscopy, microhardness, and Rockwell C hardness measurements, SEM, and microprobe analysis. Tests are also planned to determine the weld fracture toughness and crack growth rate.

In addition to the microstructural/property relationships, interaction between properties and additional factors such as: (1) filler metal composition, (2) linear heat input, (3) weld joint design, (4) base metal composition, and (5) weld reinforcement were examined. A mass balance approach, neglecting losses of base metal and filler metal alloying elements, resulted in a rule of mixtures equation in terms of the base metal amount of alloying element (X_{BM}), filler metal composition (C) given as the ratio of the amount of alloying element X in the filler metal (X_{FM}) to the amount in the base metal (X_{BM}), and the dilution ration (f_{FM}) which is the ratio of the amount of filler metal to the total amount of fused metal. The equation is

$$X_{WM} = X_{BM}\left[1 + f_{FM}\,(C-1)\right] \qquad (1)$$

where X_{WM} is the amount of element X in the weld metal. Since the mechanical properties of the weld metal depend on composition (X_{WM}), it becomes important to know how the composition varies. Equation (1) shows that X_{WM} depends strongly on f_{FM} and C, the filler metal composition parameter. f_{FM} depends on several base metal thermal properties and the weld parameters heat input (Q) and travel speed (U). A possible relationship for f_{FM} is

$$f_{FM} = \frac{A_j + A_R}{B\ (Q/U)^M} \quad (2)$$

where: A_j = joint cross-sectional area
A_R = weld reinforcement cross-sectional area
M, B = constants depending on materials and welding process (M is of order 1.)

From Equations (1) and (2), it is clear that when Q/U increases f_{FM} will decrease and, since $0 \leq C \leq 1$, X_{WM} will increase for a given X_{BM}. Such changes can significantly change the weld mechanical properties.

RESULTS

Light microscopy and microhardness measurements of the HP 9-4-30 welded with a straight polarity plasma arc (SPPA) process in two passes showed several characteristic microstructures. The solidification substructure was cellular dendritic with an average cell size of about 0.030 mm. Strong microsegregation was evident in the interdendritic regions. The HAZ showed large prior austenite grains (about 0.12 mm grain diameter) near the fusion line with very small grains nearer the base metal. The hardness of the FZ and HAZ without any post weld heat treatment (PWHT) was 54-55 hardness Rockwell C (HRC) while the base metal hardness was about 48 HRC. Because of grain size variation and carbide dissolution the hardness varied within the HAZ. Subsequent passes tended to preserve aspects of the solidification substructure from the prior pass, but did result in tempering parts of the prior pass FZ and HAZ. This tempering reduced the hardness to near base metal values. However, the region in the base metal adjacent to the HAZ underwent overtempering and resulted in a narrow softened region of about 44 HRC. This region was only 2 mm wide. The hardness readings also indicated a distinct pass-to-pass hardness difference in the fusion zones. This occurred because the filler metal was very close in composition to HP 9-4-20 with 0.20 percent C, while the base metal had about 0.30 percent C. The mixing of filler metal and base metal gives a second pass weld metal composition close to that of the filler metal. This reduced carbon content caused a significant reduction in hardness of the second pass FZ. Equation (1) quite accurately predicted the second pass FZ carbon content and confirmed the possible problem associated with pass-to-pass composition differences.

The microstructural/property analysis completed to this point indicates three areas of possible concern: (1) the microsegregation in the FZ solidification substructure which will tend to reduce ductility and toughness from base metal values, (2) the narrow overtempered zone in the base metal adjacent to the HAZ, and (3) the compositional variations from pass-to-pass due to dilution and filler metal composition. Careful control of joint design, filler metal composition, and welding parameters will be required to reduce this pass-to-pass variation. Solidification substructure can also be influenced by weld parameters. For example, as Q/U is decreased the cooling rate will increase and result in a finer solidification substructure which should give a tougher, more ductile material. However, note that a reduced Q/U will increase f_{FM} and thus reduce X_{WM} and consequently strength, while perhaps enhancing toughness and ductility. Thus, trade-offs among weld parameters, filler metal composition, and joint design will be required to optimize the final weld metal properties.

RECOMMENDATIONS

The following recommendations are offered:

(1) The currently planned subsize tensile, K_{IC}, da/dN tests should be very important in understanding the fracture process. Fractures surfaces should be examined and related to FZ microstructure.

(2) Babcock and Wilcox is planning to vary joint design, filler metal composition, and number of passes. This should be monitored carefully to determine dilution and pass-to-pass compositional variations.

(3) The overtempered zone should be examined in more detail as it relates to the actual state of stress in the joint.

Overall the HP 9-4-30 appears to be very weldable.