Welding of Maraging Steels

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Abstract. Maraging steels are iron-nickel alloys designed to combine high strength with good fracture toughness. The properties are achieved through the age-hardening of low carbon martensite that forms when the steels are cooled from the austenitizing temperatures. The martensite forms independently of cooling rate and is relatively soft (approx. Rc 30), but when it is aged at approximately 900° F it hardens considerably through the precipitation of intermetallic compounds.

From the weldability point of view, the most important feature of maraging steels is the fact that they are relatively soft after cooling from the austenitizing temperatures. This means that the heat-affected zones are softened by the heat of welding with the result that the residual stresses are lowered and there is less tendency for hydrogen cold cracking. A postweld aging treatment raises the strength of the joint close to the plate strength and the toughness of the heat-affected zone usually matches that of the plate.

The filler wires used to weld maraging steels have compositions very similar to those of the base plates. The strengths of welds depend very little on the process used to make them; most processes can produce welds with joint efficiencies exceeding 90%. The weld toughness, however, varies with the welding process. Of the more widely used processes, the gas tungsten-arc produces the best weld toughness in maraging steels. Lower values are seen in welds made with the gas metal-arc, electron beam, and flux-shielded processes. In order to obtain the best properties it is advisable during welding to:

(a) Avoid prolonged times at elevated temperature.
(b) Avoid preheat and keep interpass temperatures below 250° F.
(c) Use minimum weld energy inputs.
(d) Avoid conditions causing slow cooling rates.

In addition, every precaution should be taken to keep the welds as clean as possible since the toughness decreases as the purity decreases.

In this report a general description of the metallurgical conditions involved in welding maraging steels is followed by a detailed discussion of the usefulness of a variety of processes. Important parameters are discussed, procedures are recommended, and the properties that can be expected from the joints are outlined.

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I. Introduction

The introduction of the first maraging steels in 1960 aroused great interest because they combined good toughness and ease of fabrication with very high strength.[1] Other maraging steels with these properties have been developed since and have also received considerable attention. Towards the end of 1967 it was estimated[2] that over 100 technical papers had appeared in the open literature and there were a large number of unpublished reports. Table 1 gives the types, compositions, and mechanical properties of the steels that are available now. The first five alloys listed employ cobalt-molybdenum strengthening with titanium as a supplemental hardener. The sixth (12-5-3) was designed with nuclear applications partly in mind and so cobalt was deliberately omitted. This alloy is hardened with chromium, molybdenum, titanium, and aluminum.[3]

For the optimum strength and toughness such elements as carbon, silicon, manganese, sulfur, and phosphorus are restricted to low levels.[4] The maximum amounts specified are (in wt. %): carbon 0.03, silicon 0.1, manganese 0.1, sulfur 0.01, phosphorus 0.01.

Since the same metallurgical principles apply to all the grades the steels can be considered as a family of low carbon iron-nickel alloys containing a variety of hardening elements. Their name, "maraging," is derived from the heat treatment which involves the age hardening of low carbon martensite.

II. Physical Metallurgy

There have been several extensive discussions of the physical metallurgy of maraging steels, including a fine complete review.[5] Consequently, the metallurgical principles outlined in this section are restricted to those that have some bearing on the welding of maraging steels.

The usual way to heat treat maraging steels is to anneal at approximately 1500° F, air cool to room

Table 1-Nominal Compositions and Mechanical Properties of Maraging Steels

Maraging steel grade	Nominal composition, % Ni	Cr	Co	Mo	Ti	Al	Minimum values for sections less than 100 sq. in. Y.S., ksi	U.T.S., ksi	Elong., %	R.A., %	Impact toughness (CVN), ft-lb
18Ni(200)	18.0	...	8.5	3.2	0.2	0.1	200	210	12	55	35
18Ni (250)	18.0	...	8.0	4.8	0.4	0.1	230	240	6	35	20
18Ni(300)	18.5	...	8.7	5.0	0.6	0.1	275	280	6	30	15
18Ni (350)[a]	17.5	...	12.5	3.8	1.7	0.1	350	355	5	25	8
	18.0	...	11.8	4.6	1.3	0.1					
Cast 17Ni	17.0	...	10.2	4.6	0.3	0.1	230	240	6	30	10
12-5-3	12.0	5.0	...	3.0	0.2	0.4	180	190	14	60	50

[a] The two compositions are from different suppliers.

temperature, and then age at about 900° F. The physical metallurgy of maraging steels can be conveniently discussed in relation to the structures and properties that accompany these steps.

Solution-Annealed Maraging Steels

Although the 18% Ni maraging steels are fully austenitic above 1350° F[6] higher annealing temperatures are generally used to insure that the precipitates go into solution and that any residual fabrication stresses are removed .[7] On cooling, the austenite transforms to low carbon iron-nickel martensite that has a body-centered cubic structure with no evidence of tetragonality.[1] Thin film microscopy has shown the structure to be untwinned with dense tangles of dislocations .[8,9] This type of martensite is relatively soft (approx. Rc 30) and tough. [10] Since the austenite to martensite tranformation takes place at fairly low temperatures (the M_S of the 18Ni (250) grade is approx. 310° F) where diffusion controlled processes are not favored, the martensite forms by a diffusionless shear process.[1] An important practical benefit is that martensite is formed at all cooling rates and therefore in all section sizes.[6] The common concepts of hardenability do not apply to maraging steels.

Although it forms at low temperatures, the iron-nickel martensite can be reheated to fairly high temperatures before it transforms back to austenite (Fig. 1). Maraging steels make use of this hysteresis to age-harden the martensite.

Age-Hardening

When the martensitic structure is aged around 900º F, its strength increases. The strength of the 18Ni (250) grade more than doubles on aging at 900º F for 3 hr. Since the strengthening precipitates are small and not easily identified by direct means, there has been a great deal of discussion as to the exact strengthening mechanism.[5] The prevailing opinion is that the 18% Ni grades are strengthened with precipitates of Ni_3Mo and a secondary titanium precipitate, possibly Ni_3Ti.[8, 11, 12] Ribbon-shaped Ni_3Mo is the major precipitate with the secondary Ni_3Ti being uniformly distributed as spherical particles throughout the matrix. Cobalt accelerates the rate of precipitation but does not itself precipitate. It is thought that cobalt reduces the solubility of molybdenum in iron-nickel alloys, thereby producing a larger amount of finely dispersed precipitate which increases the strength.[13] The role of cobalt is crucial because in a unique combination with molybdenum it makes it possible to maintain good toughness at strengths up to above 300 ksi. Alloys that do not employ this combination appear to embrittle around 220 ksi (Fig. 2).[13] The commercial alloys that do not contain cobalt have been used so far at strength levels up to approximately 200 ksi. The precipitates in these alloys have not been studied in detail.

The changes in hardness that occur when an 18% Ni steel is aged at various temperatures are shown in Fig. 3.[6] It is clear why temperatures near to 900º F are those commonly used for aging. At 900º F, the

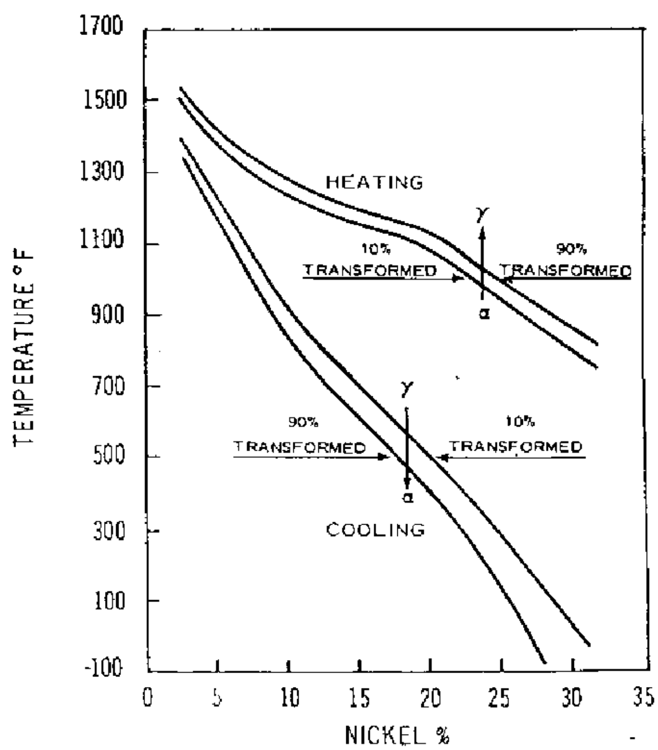


Fig. 1–Iron-nickel transformation diagram (after Jones and Pumphry)

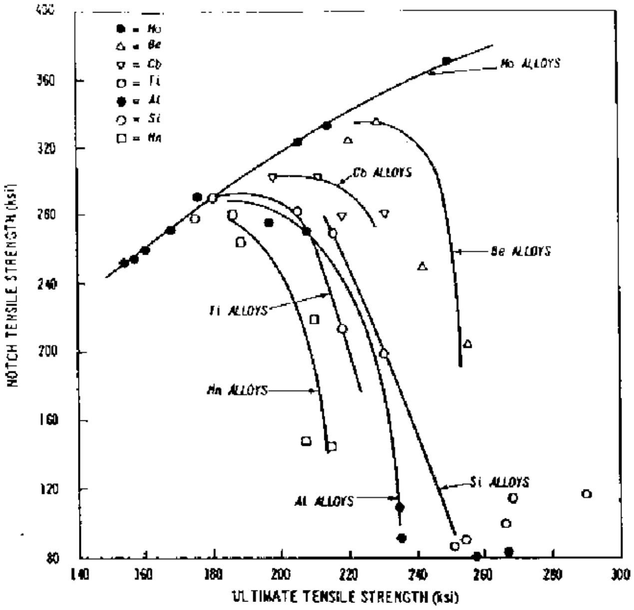


Fig. 2–Notch tensile strength vs. ultimate tensile strength of Fe- 18Ni-8Co-X quarternary alloys

hardening occurs rapidly, yet at the maximum hardness, the curve stays flat to approximately 100 hr. At 800° F the reactions are much slower, while at 1000 and 1100° F, the steels harden rapidly but soon soften. There is evidence that the softening is caused by a combination of classical overaging and the formation of soft, stable austenite. [14]

Reversion to Austenite

The diffusion controlled formation of austenite in maraging steels is called "austenite reversion." Its occurrence can be understood from an examination of the iron-nickel equilibrium diagram (Fig. 4). At temperatures in the two-phase region, the martensite breaks down to α' ferrite and γ' austenite, and partitioning of the alloying elements occurs: The γ' becomes alloy-rich and does not fully transform to martensite on cooling.

Local changes in matrix composition can encourage the formation of austenite. There is evidence, for example, that when the steels are overaged the precipitate Ni_3Mo goes into solution and is replaced by Fe_2Mo.[15] This enriches the matrix locally in nickel and encourages the formation of austenite.[16] Soft austenite lowers the strength of the steels and therefore should be avoided. This is accomplished by annealing at temperatures well above the two-phase region and aging at temperatures sufficiently below it.

III. Welding Metallurgy

The Heat-Affected Zone

It is convenient to consider the heat-affected zone in maraging steels as three separate zones (Fig. 5). Nearest to the weld is a zone (A) that was heated into the fully austenitic region by the heat of welding and transformed to martensite on cooling. Next to this is a narrow band (B) that was heated into the two-phase austenite + ferrite field. Finally there is a zone (C) that experienced temperatures from approximately 900° F to just above ambient.

Zone A. The peak temperature experienced at the interface between zones A and B has been measured at approximately 1350° F[17,18] so that zone A extends from the fusion line to approximately the 1350° F isotherm. During welding, the metal in this zone is heated into the fully austenitic region and then cooled. Regardless of the cooling rate, the structure after welding is a low carbon, iron-nickel martensite with a hardness of approximately Rc 30 or 350 VPN (Fig. 6). If the steel was in the aged condition before welding, its strength in zone A will have been reduced by the heat of welding (Fig. 7). If the steel was welded in the annealed condition, the strength in zone A is hardly altered by the process of welding (Fig. 8).[19] Both these figures also show that when the joint is aged after welding, the strength of zone A increases almost to the strength of the aged plate. There is a slight strength reduction in the coarse-grained region (Fig. 9) which is in line with the findings of Floreen and Decker[6]) who observed that very high annealing

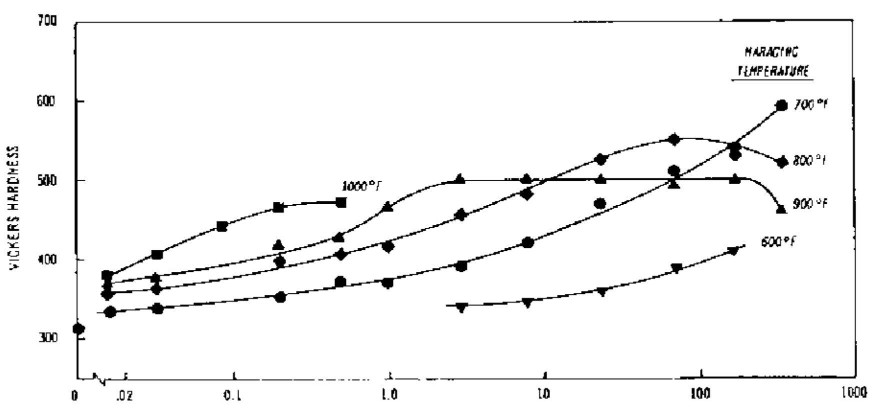


Fig. 3–Effect of maraging on hardness of 18% Ni steel. Initially annealed at 1800° F

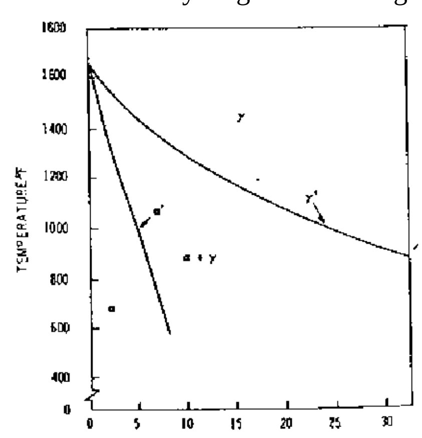


Fig. 4–Iron-nickel equilibrium diagram (after Owen and Liu)

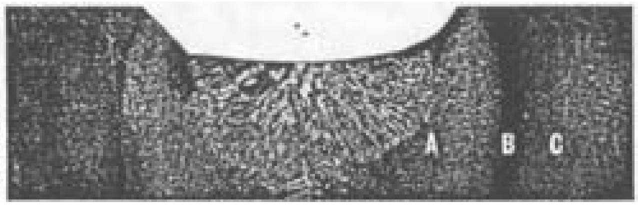


Fig. 5–One-pass weld showing regions of heat-affected zone. Etchant: Lepito's Reagent. X4 (Reduced 40%)

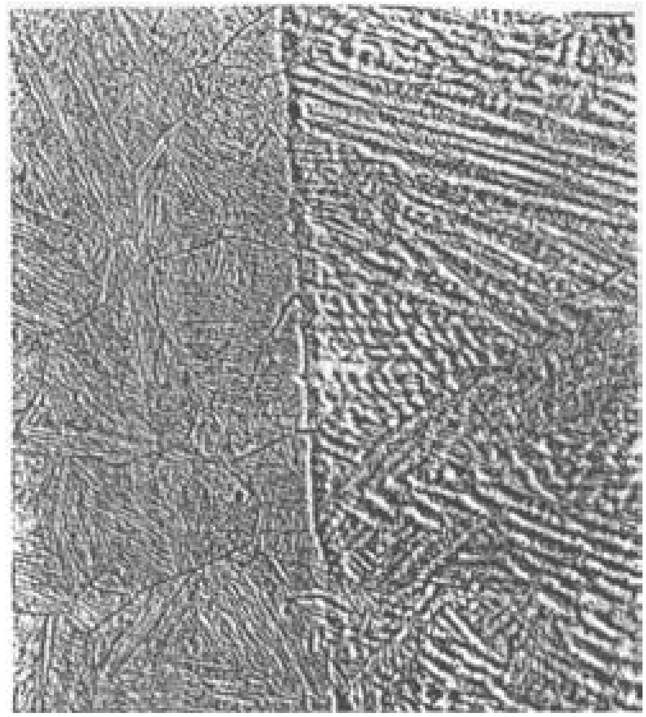


Fig. 6–The microstructure near the fusion line of a weld in 18Ni (250) maraging steel. Etchant: 10% chromic acid electrolytically. X500 (Reduced 15%)

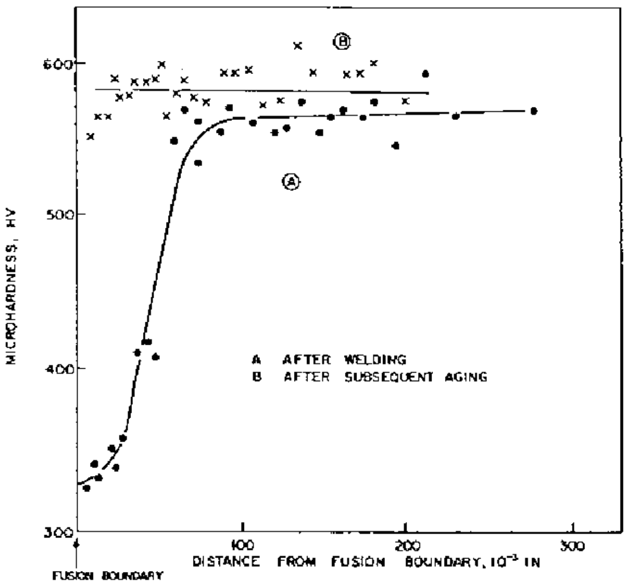


Fig. 7–A microhardness traverse of the heat-affected zone *of* a weld made on aged 18Ni (250) maraging steel

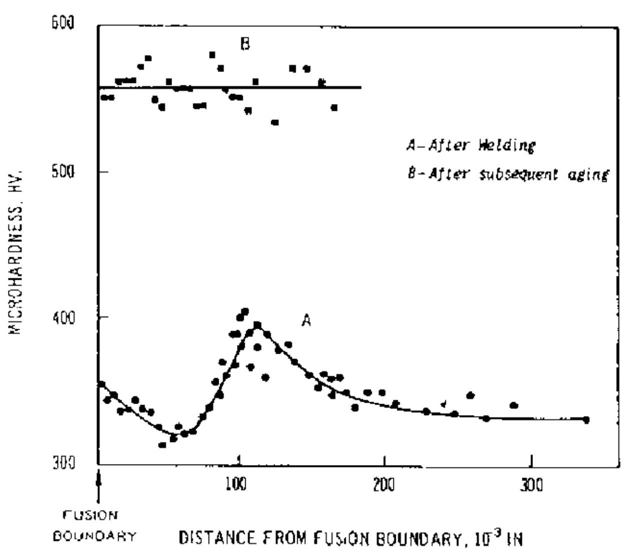


Fig. 8-A microhardness traverse of the heat-affected zone of a weld made on 18Ni (250) maraging steel in the as-annealed condition

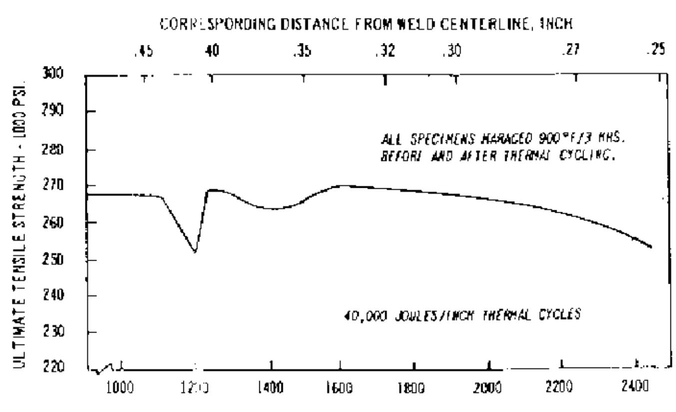


Fig. 9–Ultimate tensile strength of the synthetic heat-affected zone as a function of peak temperature

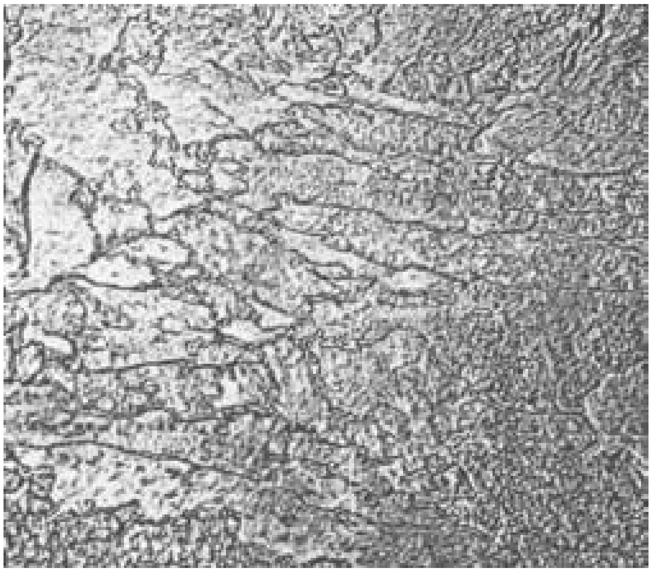


Fig. 10–Fine dispersion of austenite in martensite in the heat-affected zone dark band. Etchant: modified Fry's Reagent. X20.000 (Reduced 25%)

temperatures caused a slight decrease in strength.

Zone B. The comparatively small volume of metal that is heated to a maximum temperature in the two-phase region (approximately 1350 to 1100° F) is often termed the eyebrow region or dark band because it etches black. It is martensitic with a fine dispersion of stable, reverted austenite (Fig. 10). The formation of this structure has been studied by Petersen[18] using the Gleeble equipment. He heated samples of 18Ni (250) maraging steel at heating rates from 100° F/sec to 800° F/sec and followed the transformation with a high speed dilatometer. At the higher heating rates the martensite transformed to austenite by a shearing mechanism. At heating rates less than 400° F/sec, diffusion controlled formation of austenite occurred before the shearing reaction took over at higher temperatures. This time-dependent transformation is the austenite reversion discussed earlier. The product of the reversion is a soft, stable austenite that does not harden when the joint is aged. In consequence, the dark band remains weaker than the rest of the heat-affected zone structure. Just how much weaker it is will depend on the amount of austenite it contains. Since the amount increases with time at temperature, and therefore with heat input, one would expect the strength to decrease as the heat input increases. This trend is shown in Fig. 11.

Samples cycled in the Gleeble to a peak temperature of 1200° F at a heat input of 40,000 joules/in. and then reaged had yield strengths approximately 10% less than that of the unwelded plate (Fig. 9). This is true for all grades (Fig. 12). Repeated cycling to the temperature causes further loss in strength.[20] This is to be expected since more austenite forms with each cycle. There is also evidence that reverted austenite forms more readily when there is already some austenite in the structure.[16]

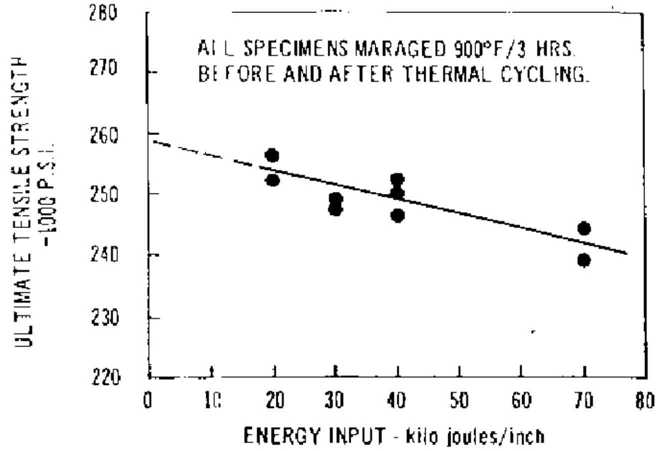


Fig. 11–Strength of specimens cycled to 1200°F peak temperature at varying energy input values

In actual welds the width of the dark band is an important factor because the thinner the band the more effectively it is supported by surrounding stronger material. Here again low heat inputs would be expected to be beneficial. In practice these heat-affected zone considerations are often not very important because transverse tensile samples frequently fail in the weld metal at joint efficiencies of 90 to 95% depending on the grade being welded. There have however been instances of heat-affected zone failures at strengths corresponding to joint efficiencies of 80 to 85%. These occurred when high heat inputs were used.[17, 21, 22] Consequently control of heat input in order to minimize the dark zone is good practice and is recommended.

Zone C. This zone is affected very little by the heat of welding. The end nearest the weld will be heated into the aging temperature range but the small

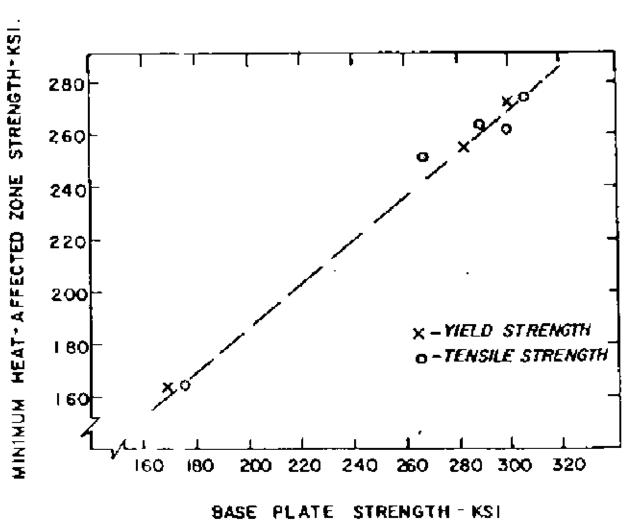


Fig. 12–Effect of a 1200° F peak temperature on the strength of maraging steels. (Samples cycled in Gleebte using a 40.000 joules/in. heat input)

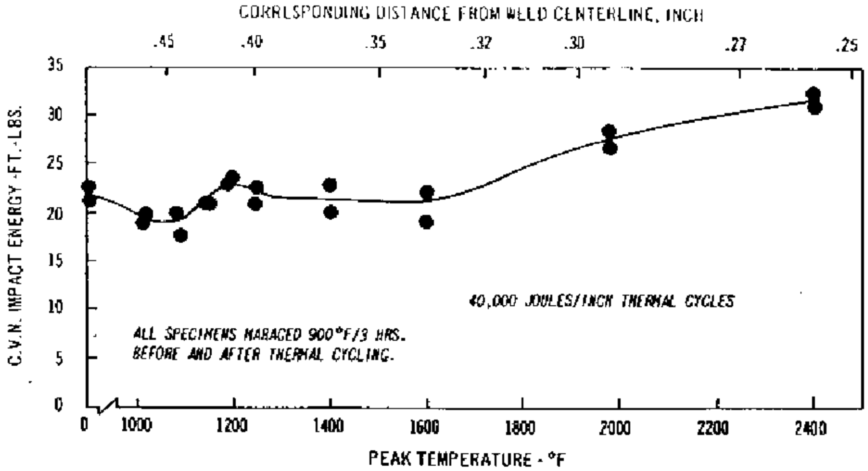


Fig. 13–Charpy V-notch impact resistance of the synthetic heat-affected zone

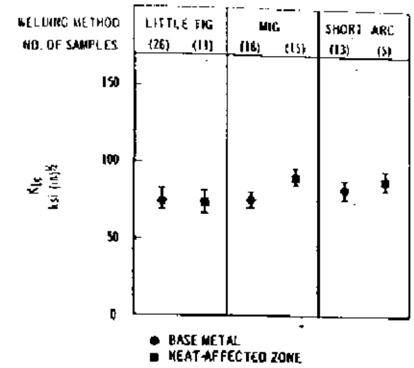


Fig. 14-K_{Ic} of air-melted ¾ in. thick, 250 ksi maraging steel; bars cut transverse to rolling direction

amount of extra aging is not sufficient to be readily noticeable. For practical purposes, this third zone can be considered as the unwelded plate.

The Toughness of *the Heat-Affected Zone.* The impact toughness of the various structures of the heat-affected zone produced by cycling in the Gleeble is shown in Fig. 13. It is similar to that of the unwelded plate except in two regions where the slightly lower strengths are accompanied by somewhat higher toughness values.

The toughness measured on bars notched in the heat-affected zones of actual welds substantiate the Gleeble results. For example, the plane strain fracture toughnesses of the heat-affected zones of both submerged-arc and gas tungsten-arc welds in 18Ni (250) maraging steel were similar (approx. 85 ksi (in.)$^{1\ 2}$) and higher than that of the plate (approx. 75 ksi (in.)$^{1/2}$).[23] Kies, et al.[24] in a thorough study of the toughnesses of maraging steel weldments, tested a large number of specimens from joints made by several processes. Figure 14 is typical of their results and shows the heat-affected zones to be slightly tougher than the unwelded plate.

The Weld Deposit

The Structure of *the Weld.* The compositions of the filler wires used to weld maraging steels are usually very similar to those of the base plates. Consequently both the weld and plate have the same basic structure in that both consist of a low-carbon martensite matrix which on aging hardens through the precipitation of intermetallic compounds. Thin film microscopy of 18% Ni welds has confirmed this similarity[25], although it also showed the weld structure to be more complex than that of the plate. The weld had a higher dislocation density and contained regions of austenite.

The structure of an aged weld in 18Ni (250) maraging steel consists of white pools of austenite, dark etching regions around the austenite, and the martensitic matrix structure (Fig. 15). The austenite pools are not present in a one-pass gas metal-arc weld when it is examined as-welded. They appear when the weld is aged (Fig. 16).

In a homogeneous composition stable austenite is formed most readily around 1200° F.[6] In welds, however, stable austenite pools will form at lower

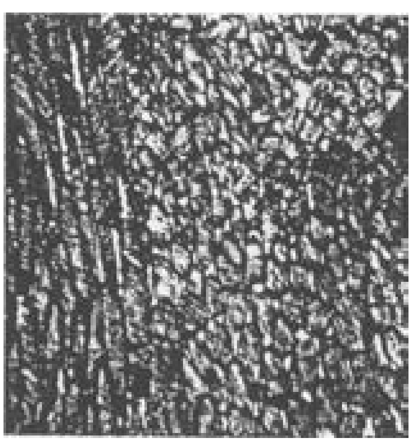


Fig. 15–The microstructure of a gas metal-arc weld made with a filler wire of nominal composition (wt. %): 18Ni, 8Co, 4.5Mo, 0.5Ti. 0.10Al. Weld aged at 900° F for 3 hr. Etchant: modified Fry's Reagent. X 1000 (Reduced 45%)

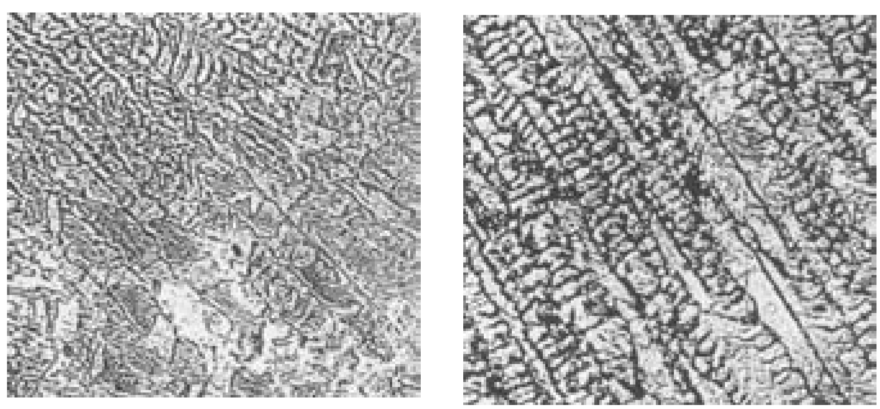
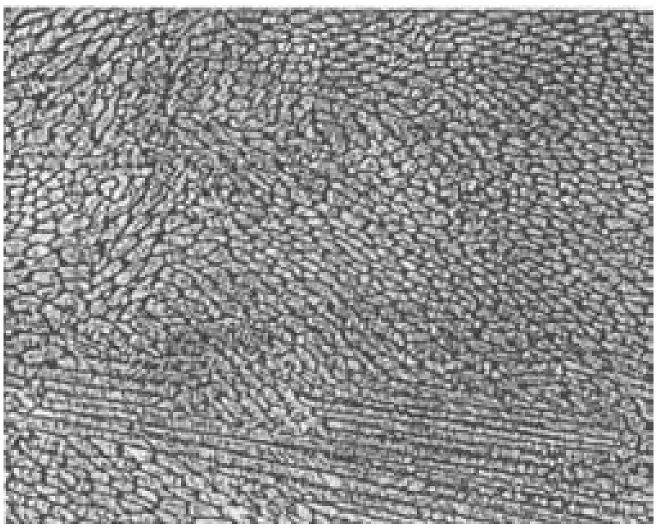


Fig. 16–The microstructure of a one-pass weld made with the gas metal-arc process. (a) as-welded, (b) after aging at 900° F for 3 hr. Etchant: modified Fry's Reagent. X250 (Reduced 30%)

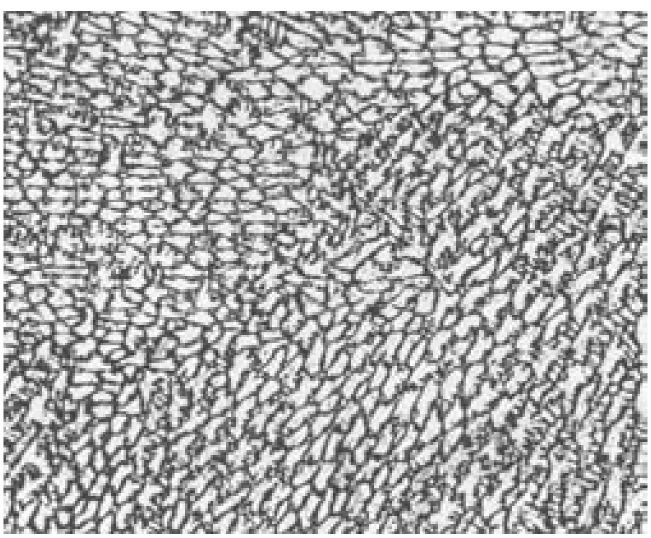
temperatures; e.g., on aging 900° F for 3 hr. The pools form in regions to which the alloying elements have segregated. This means that the presence of these elements in greater than normal quantities can cause a lowering of the reversion temperature.

Microprobe analysis has shown the hardening elements molybdenum and titanium segregate the most.[24,26] This suggests that if the amounts of these elements in the filler wire were reduced, there would be less of them in the intercellular regions and, therefore, less tendency for austenite formation. That this is true can be seen by a comparison of 18Ni (250) and 18Ni (200) welds. The lower strength grade contains less molybdenum and titanium and is substantially free of austenite pools (Fig. 17).

Effect of Structure on. Properties. Attempts to relate the properties of welds to their metallurgical structure have centered on the effect of the pattern of segregation. There has long been concern that



(a)



(b)

Fig. 17–The structures of (a) 18Ni (200) and (b) 18Ni (250) welds after aging Note difference in austenite pools. Etchant: modified Fry's Reagent. X250 (Reduced 33%)

the soft austenite adjacent to the hard martensite might be detrimental to toughness.[27] Corrigan showed that the ductility of the welds could be improved by high temperature homogenization treatments.[28]

It has been suggested that the dark etching regions, since they are solute enriched, could contain particles that act as fracture nuclei .[29] These nuclei then link-up by deformation and failure in the intracellular matrix structure. Examination of the fracture profiles of broken notched samples from TIG welds has led others to the somewhat different conclusion that the cell boundaries themselves are the preferred path for fracture.[23]

A study of the crack path in an unbroken but cracked tensile specimen from a 18Ni (250) weld showed that the crack was progressing by the joining up of voids or microcracks in the austenite pools (Fig. 18). The austenite was failing prematurely (Fig. 19), with the crack that linked two voids appearing to take the shortest path between them.[30] There was evidence that the voids and cracks were associated with inclusions which were present in the center of the austenite pools (Fig. 20).

Filler wire compositions were devised that produced welds with little or no austenite. At the same strength level, the toughness of welds with little austenite was much better than that of austenite containing welds. This was true for both MIG and TIG welds.

The dark bands discussed previously with reference to the heat-affected zone are also present in multipass welds (Fig. 21). In regions where several of them overlap, the strength can be reduced significantly. For example, the strength at the bottom of a TIG weld made with many passes can be noticeably lower than the strength measured at the top of the same weld. Welds made with fewer passes are unlikely to be affected in this way because the black bands are more widely dispersed.

It is evident from this discussion that the segregated cast structure has important influences on the mechanical properties of the welds made with all of the fusion welding processes. Other influential factors such as grain structure and inclusion level vary a great deal with the welding process, and in fact this variation is responsible for the differences in the properties of welds made by different processes. These factors will be considered later when the individual processes are discussed.

Residual Stresses in Maraging Steel Weldments

The residual stress system measured in maraging steel weldments is unusual. Whereas the conventional pattern of residual stresses shows the stresses to be at a maximum and tensile along the weld centerline with tensile stresses extending into the heat-affected zone (Fig. 22), the pattern in maraging steels shows the centerline stresses to be compressive .[31, 32] They only become tensile at some distance from the weld fusion line (Fig. 23). An explanation[31] that has been put forward to account for this stress pattern is that,

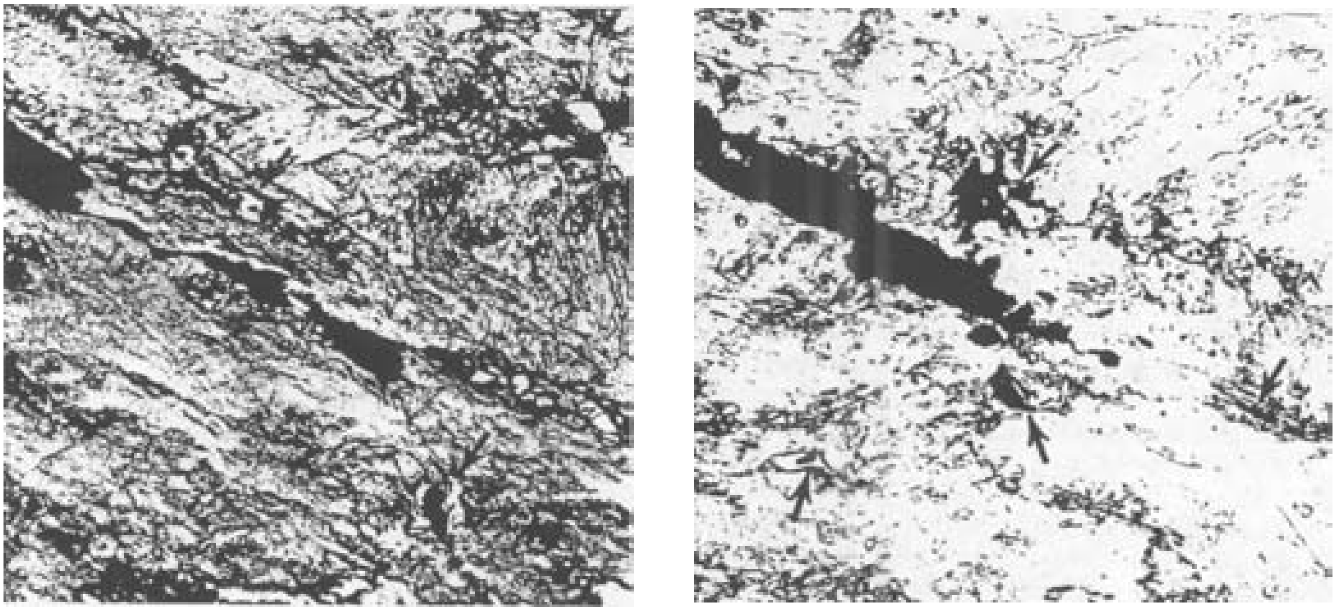


Fig. 18–Two examples showing failure of austenite pools in the region of a propagating crack (see arrows). Etchant: modified Fry's Reagent. X 1000 (Reduced 15%)

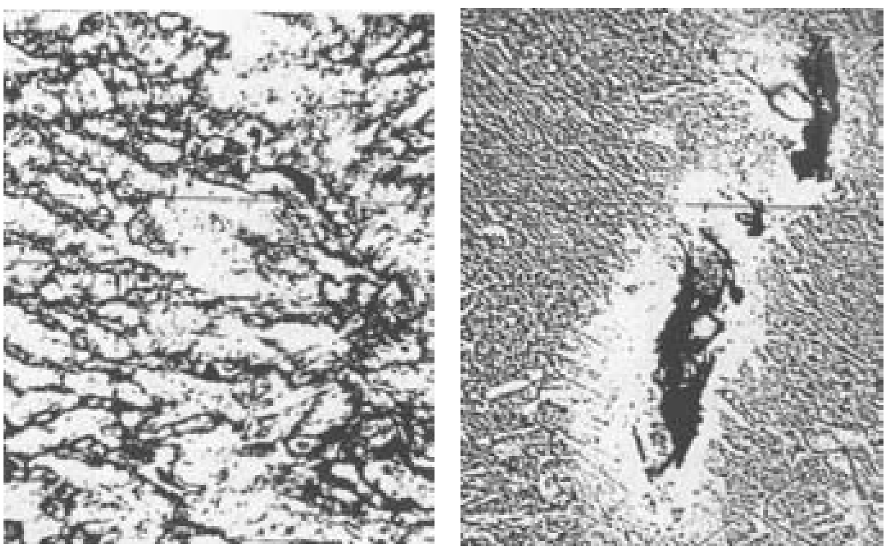


Fig. 19–Cracks and voids in austenite pools ahead of a propagating crack. (a) optical micrograph, X750 (reduced 40%) (b) parlodian replica. X7000 (reduced 40%). Etchant: modified Fry's Reagent

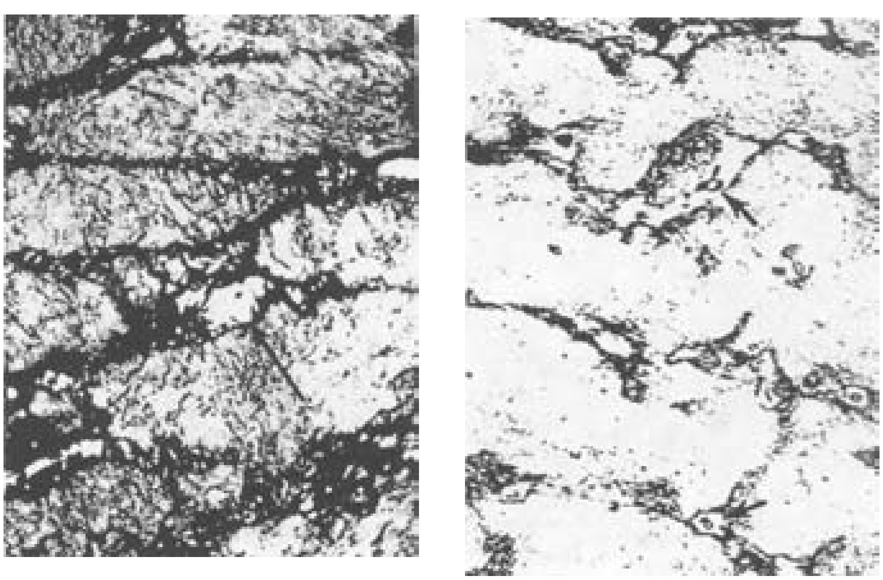


Fig. 20–Cracking in an austenite pool associated with an inclusion. Etchant: modified Fry's Reagent. Left X2000. right X 1000 (Reduced 30%)

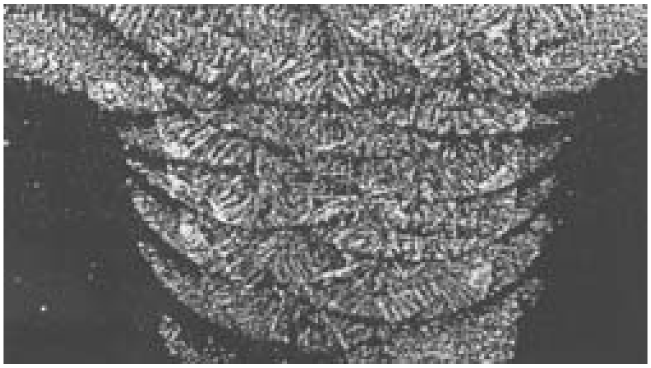


Fig. 21–Dark bands in the weld. Etchant: Lepito's Reagent. X3 (Reduced 35%)

during cooling, residual tensile stresses are set up in the usual way because of the hindered contraction. But, when the austenite to martensite transformation takes place, there is a resulting increase in volume that sets up opposing compressive stresses that are large enough to neutralize and overcome the tensile stresses. It is because the transformation occurs at comparatively low temperatures that these compressive stresses are so dominant. The temperature is too low for any significant stress relief to occur.

This stress pattern should mean that the danger of cold cracking will be lessened because close to the fusion line the stresses would be compressive and therefore relatively harmless.

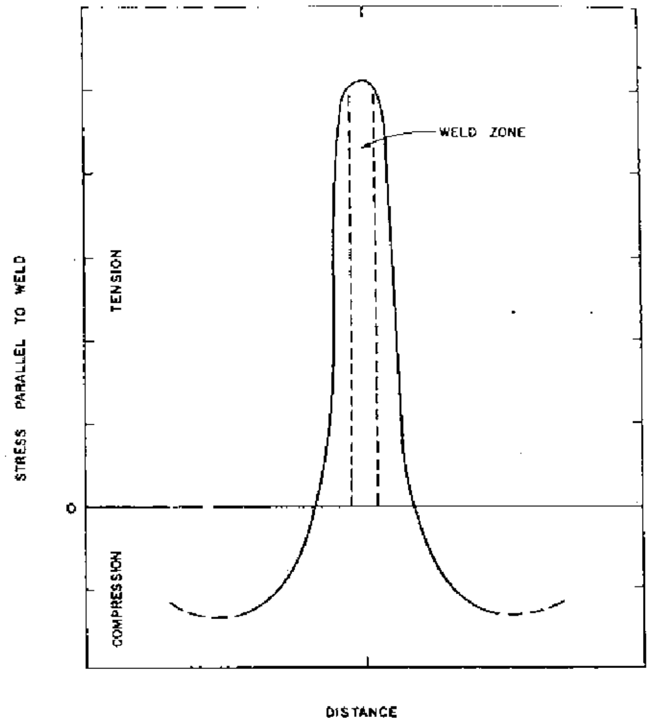


Fig. 22–The "conventional" residual stress pattern in the immediate vicinity of a weld

Hydrogen Embrittlement in Weldments

The susceptibility of maraging steel weldments to cold cracking has been examined by Boniszewski.[33] He charged notched samples of 18Ni (250) steel with hydrogen at approximately 2000° F and quenched them to simulate the cooling rates in a heat-affected zone. The samples were then loaded statically and the time to failure plotted versus stress. The stress that the 18Ni (250) steel was able to support without failure was substantially higher than that measured previously for a medium-carbon low-alloy steel that had been similarly treated.[34] The two steels had similar strengths in the fully heat treated condition, but after the quench the carbon-hardened steel would be very hard (approx. Rc 60) and strong, while the maraging steel is comparatively soft (Rc 30). This difference in their as-quenched strengths is the main reason for the difference in their load-carrying capacities when charged with hydrogen. Since the susceptibility to hydrogen embrittlement increases with tensile strength,[35] the relatively soft maraging steel should be less prone to hydrogen embrittlement.

Even in the fully hardened condition, maraging steels have shown less susceptibility to hydrogen embrittlement than carbon-hardened steels of the same strength, and they recover their properties much faster when they are baked at low temperatures.[36]

The combination of low susceptibility to hydrogen embrittlement and residual stresses that are com-

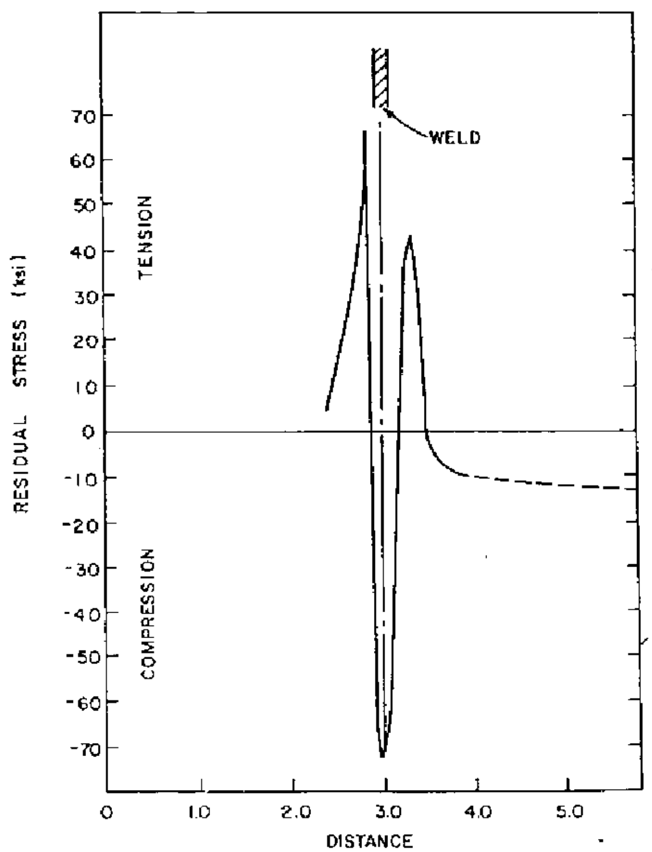


Fig. 23–The residual stress pattern in a 12-5-3 maraging steel weld

pressive in the proximity of the weld would be expected to make the chance of cold cracking in maraging steel welds fairly remote.

Incidence of Cracking

Cold Cracking. When tested at maximum restraint in the Lehigh Restraint Test, 18Ni (250) maraging steel did not crack even when either 5% hydrogen or 1% water was added to the argon shielding gas.[37] Its performance in Controlled Thermal Severity tests was also said to be good.[38]

On the other hand, there have been instances of transverse cold cracking in the cast structure of a weld, in spite of the favorable stress system discussed earlier. In early development studies, Witherell and Fragetta[39] saw transverse cracks in gas metal-arc welds made in 1 in. thick 18Ni (250) plate with air-melted filler wire. The cracking was avoided when the filler wire was baked before use, and also when vacuum-melted wire was used. Very similar observations. have been reported recently by Roberts.[40] When gas metal-arc welding 18Ni (200) maraging steel, he encountered transverse cracking in the weld. Inquiries uncovered the fact that the particular batch of wire he was using had not been vacuum annealed during preparation. All subsequent batches were vacuum annealed and no further cracking was encountered.

These results emphasize the importance of controlling the filler wire hydrogen content. Some workers have reported[41] that cracking can be expected when the hydrogen content of the weld deposit exceeds approximately 5 ppm. Others felt that 3 ppm was the safe limit and suggested that there should be no more than 5 ppm in the filler wire.[42,43] These latter, more stringent, requirements appear to have been widely accepted.

Hot Cracking. As in other alloys, the incidence of hot cracking in maraging steels seems to be most clearly related to such impurities as sulfur, phosphorus, and silicon. Since these elements lower the toughness of maraging steels it is recommended that they be controlled to low levels, and when they are, the alloys appear to be resistant to hot cracking. In the Huxley hot cracking test for example, a vacuum melted heat of 18% Ni maraging steel made from high purity materials had a crack susceptibility factor of zero.[44] Similarly, hot ductility testing of an 18% Ni steel showed that it was not prone to heat-affected zone cracking.[45]

However, as the Varestraint test has shown,[46] heat to heat variations can be expected. And if impurity levels are allowed to increase, cracking can be encountered. Pepe and Savage[47] used a heat of 18Ni (250) maraging steel to demonstrate "constitutional liquation" in the heat-affected zone. During welding, titanium sulfide inclusions near the fusion line started to go into solution and local regions, rich in titanium and sulfur, were formed. These took the form of grain boundary liquid films which became fissures as the weld cooled. In this regard it is interesting that in other work filler wires with titanium contents above about 0.8% produced weld metals with a tendency to hot cracking.[28] This increased sensitivity with increasing titanium content is likely to apply equally to the heat-affected zone. In consequence, cracking is more likely in the very high strength grades which employ relatively large amounts of titanium for strengthening.

When welding some of the earlier heats of maraging steels several workers encountered heat-affected zone cracks parallel to the plate surface. The cracks were along bands pf segregation in the base plates, and in many instances these bands took the form of layers of austenite containing stringers of non-metallic inclusions.[10] The heat of welding set up stresses that caused delamination of the austenite. Steels cut by plasma-arc delaminated in the same way.[41]

Changes in the plate processing techniques minimized the segregation and banding and as a result heat-affected zone cracking of this kind is no longer a major problem.

IV. General Welding Considerations

Purity and Cleanliness

Puzak, et al.[48] have recently concluded, after extensive tests, that the fracture toughnesses of high strength steels at a specific yield strength are determined primarily by the cleanliness of the materials (Fig. 24). If high toughness is needed, the materials must contain low levels of impurity elements. This applies to both welds and plates.

There has been a growing realization of the importance of purity in high-strength-steel welds and fabricators are now probably unanimous that cleanliness in materials, in joint preparation, and in the welding process is essential for the production of welds with good mechanical properties.

Preweld preparation should include cleaning the joint surfaces and surrounding areas, usually with

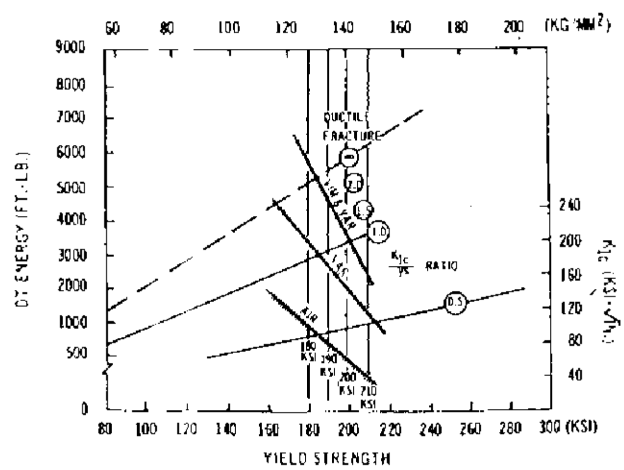


Fig. 24–The influence of melting practice on the structural performance of ultra-high strength steels. AIR = Air Melt; VAC = Vacuum Arc Remelt; VIM = Vacuum Induction Melt

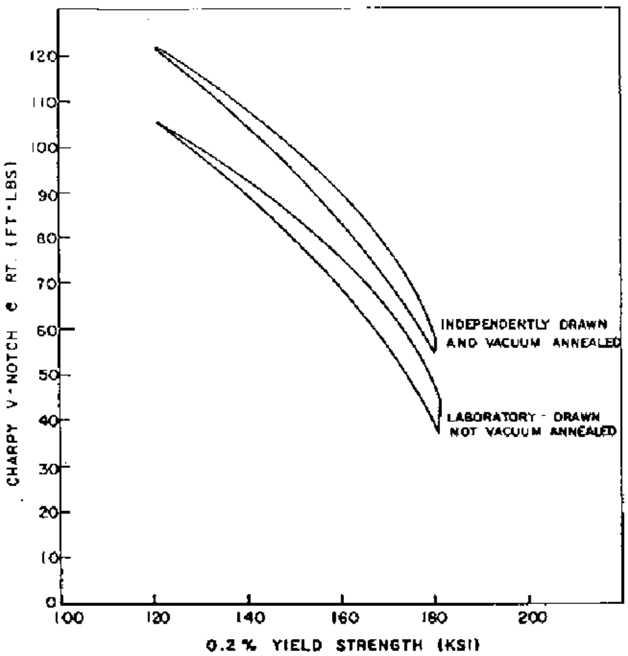


Fig. 25–The effect of wire processing on the toughness of 12-5-3 maraging steel welds

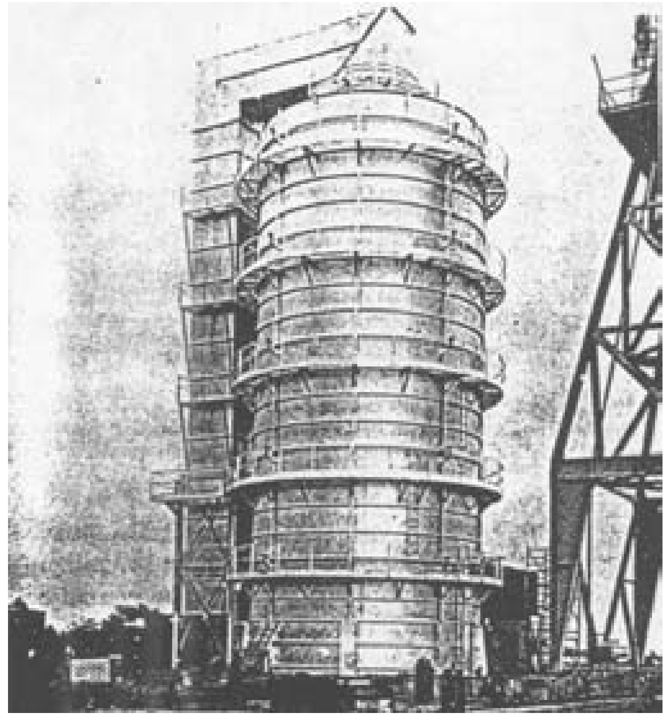


Fig. 26–Assembled 260-SL maraging furnace

clean rags and a ketone or alcohol solvent. In one instance, 200 proof anhydrous ethyl alcohol was used because the 5% moisture in the 190 proof grade contributed to weld porosity.[49] Some fabricators also go to considerable lengths to clean such items of equipment as wire feed rolls and guide tubes in order to avoid wire contamination from these sources.

Wire quality, also, is an important factor in governing weld soundness and properties.[50-52] The wire should be made from very clean material and must be processed so that surface quality is good and there is no entrapped oxide or lubricant. Such techniques as surface turning to remove up to 0.015 in. from the hot-rolled rod before drawing, are helpful in this respect. Vacuum annealing of the wire is recommended (Fig. 25), and ultrasonic cleaning has also proved useful. Finally to avoid contamination, the spooled wire is packaged and stored in dry, argon-purged, containers. The gas analysis of the wire is an indication of its suitability. Oxygen and nitrogen levels below about 50 ppm and hydrogen below 5 ppm are desirable.

The shielding gas used for the welding should be maintained pure and dry, and the lines and equipment through which it travels should be clean and free of possible leakage. Small details of shielding control such as the use of gas diffuser screens in the torch, and proper inclination of the torch in the direction of travel have been shown to be beneficial .[49] There is also evidence that auxiliary shields such as trailing shields can minimize porosity and improve the properties of the joints .[21, 50]

Tooling Considerations

Tooling requirements depend on such factors as the size and shape of the component being welded and the dimensional tolerances that must be held. The requirements thus vary from one application to the next. There are, however, two points of general importance to be kept in mind when welding maraging steels. One is the need to minimize heat input, by choosing backing and clamping fixtures that limit heating of the parent metal. The other is the fact that it is easier to restrain, size and fit-up material in the solution-annealed condition than in the fully aged condition, and thus simpler, less massive, tooling is required. Consequently when component design and furnace capacity permit, it is simpler to weld material in the solution-annealed condition and to post-weld age the entire component. A protective atmosphere is not required. This approach was applied successfully to booster cases almost 22 feet in diameter (Fig. 26). If it is not practicable to age the whole structure, maraging steels can be welded in the fully heat-treated condition and then locally aged at the weld joints by flame or resistance heating methods.

Arc Stability

There have been reports of troublesome arc instability during the welding of maraging steels. These prompted an examination of the magnetization characteristics of an 18% Ni maraging steel since the presence of residual magnetic fields in the parts being welded is known to be one cause of arc blow.[53] The study found that although greater field strengths were needed to magnetize the maraging steel, it was considerably more retentive than carbon steel and more difficult to demagnetize. The results suggest that care should be taken to ensure that the plates do not become strongly magnetized before welding.

A common way to improve arc stability when MIG

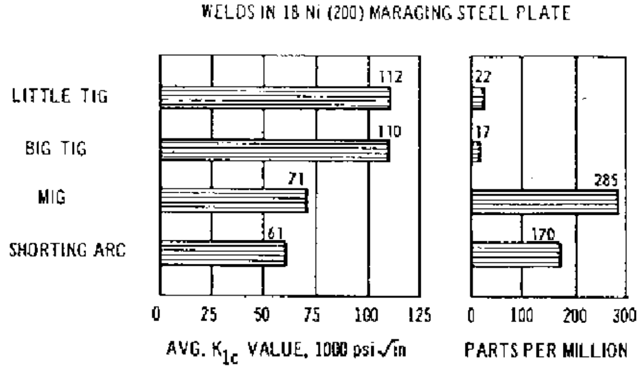


Fig. 27–Chart indicating that low fracture toughness is associated with high oxygen content of welds in 18Ni maraging steels

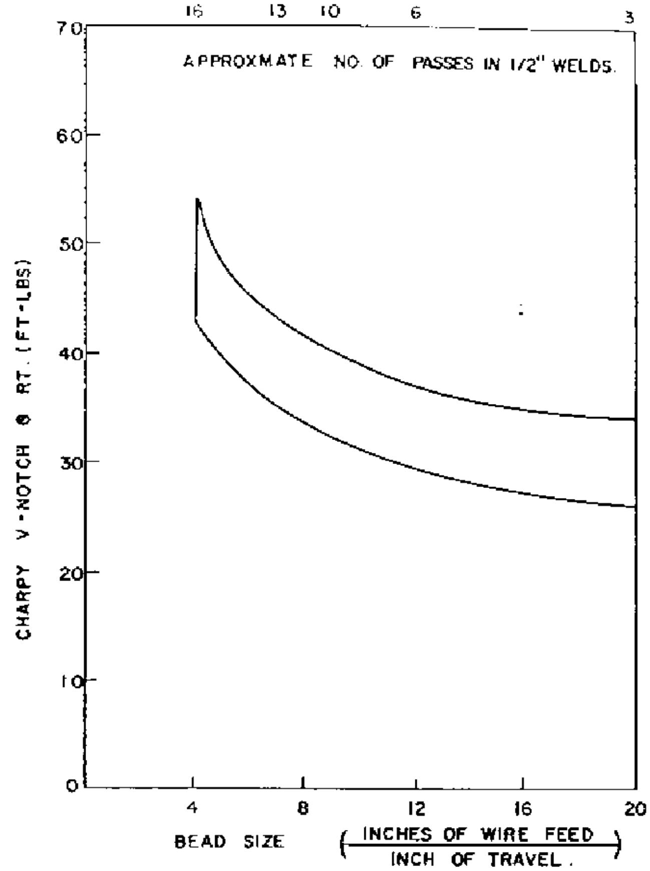


Fig. 28–Impact toughness vs. bead size for 12-5-3 inert-gas welds

welding high alloy steels is to add small amounts of oxygen or carbon dioxide to the shielding gas. These additions, however, increase the inclusion content of the weld and so tend to reduce weld toughness. The experience of Knoth and Petersens[54] illustrates these effects. They found that while MIG welds could be made satisfactorily using pure argon as the shielding gas, the arc stability was improved when oxygen was added. But, the oxygen did reduce the weld toughness; with approximately 4% oxygen, the impact toughness (CVN) of 12Ni-5Cr-3Mo welds fell from 32 ft-lb to 22 ft-lb. The data of Romine[55] show how the toughness decreases as the weld-metal oxygen content increases (Fig. 27). The high oxygen contents of the MIG and shorting-arc welds of this study resulted from the use of a mildly oxidizing gas shield to improve arc stability.

In contrast to these studies, other people found oxygen to have no effect on toughness. Roberts, for example, observed that adding 1% O_2 to argon produced the most stable arc without affecting the toughness of 18Ni (200) welds.[40] Even with 5% oxygen in the shielding gas some workers apparently detected no loss in toughness. Others felt that 1% was too much.[56]

The disagreement on the extent to which oxygen affects toughness is understandable because the degree of the effect will depend on the purity of the materials being used to make the weld. Welds made with relatively impure materials might contain many inclusions even when pure argon is used, so that additions of oxygen would have little effect. On the other hand, small amounts of oxygen would impair the toughness of welds made with very pure materials.

It seems advisable to avoid the use of oxygen additions particularly since there is an indication that they can also increase the amount of porosity.[21] If oxygen must be added the quantity should be as small as possible. There is an indication that amounts of ½% or less can stabilize the arc without spoiling the weld toughness (Table 2).

An alternative way that has been used to overcome arc blow is to MIG weld with emmissively coated wire and an alternating current. Good arc stability and bead appearance were reported when this process was used with pure argon shielding to weld maraging steel, but so far the technique has not been widely applied.[57]

Control of Heat Input

High heat inputs should be avoided when welding maraging steels because they are usually associated

Table 2-Effect of Oxygen Additions to the Shielding Gas on the Mechanical Properties of a 1 in. Thick 12-5-3 Gas Metal-Arc Weld[a,b]

Shielding gas	*Y.S., ksi*	*U.T.S., ksi*	*Elong., %*	*R.A., %*	*Location of fracture*	*Impact toughness of welds (CVN), ft-lb*
Argon	179.7	189.8	11	53	Weld	34,30,35
Argon + ½% O_2	179.1	190.3	13	63	Weld	34,28,31

[a] Weld made with a 17Ni-2Co-3Mo filler wire.
[b] Samples postweld aged at 900° F/3 hr.

with large weld beads which have a coarse, segregated structure and poor toughness.[50,58] As the bead size increases the weld toughness decreases (Fig. 28), and consequently fine stringer beads are recommended. High heat inputs also involve longer times at high temperature and slower cooling rates. These encourage the formation of grain boundary precipitates particularly in the stronger grades, and this can embrittle the steels.[23] Finally, as the heat input increases, the yield strength of the heat-affected zone dark band decreases. The strength can be restored by postweld solution annealing before aging, but on large structures this is expensive and not always practicable. An advantage of maraging steels is that they do not require high temperature, post-weld treatments. An aging treatment at 900ºF is sufficient, and is the one commonly used in practice.

Sound advice on how to weld maraging steels is[27]:

1. Avoid prolonged times at elevated temperature.
2. Do not preheat; keep interpass below 250º F.
3. Use minimum possible weld energy input.
4. Avoid conditions causing slow cooling rates.

Fig. 29–First 260 in. diam rocket motor case

V. Welding by the Inert-Gas Processes

The common gas tungsten-arc and gas metal-arc processes are the ones that have been most extensively studied and applied in fabricating maraging steels. This is a direct consequence of the fact that these techniques can be well controlled and can produce the high-quality joints required in such critical applications as rocket motor cases. It would be inaccurate to suggest that there have been no problems associated with these processes, but in general, difficulties have been minimal. The large booster cases shown in Figs. 29 - 31 demonstrate how successfully these processes, particularly gas tungsten-arc, have been applied.

Gas Tungsten-Arc Welding

Most gas tungsten-arc welding has been accomplished by the standard techniques, but several newer variations of the basic process have been used as well. These are:

"*Big TIG*".[59.60] This technique uses a larger tungsten electrode (¼ in.), increased amperage, and increased welding speeds and filler metal feeds to achieve higher deposition rates. The developers have noted however[61] that its primary use is for welding material ½ in. and heavier. The deposition rate in thinner gages is sufficiently high to produce a coarse columnar-grained deposit which would be expected to have less than optimum toughness.

TIG "Hot Wire".[62] This technique differs from the more common cold-wire feed by employing an auxiliary ac power supply to melt filler metal by resistance heating. Parameters are adjusted to melt the wire just as it reaches the puddle. The use of this method increases deposition rate significantly.

"Plasma-Arc".[62,64] Though sometimes considered a separate process, plasma-arc welding is basically a gas tungsten-arc modification. The major difference

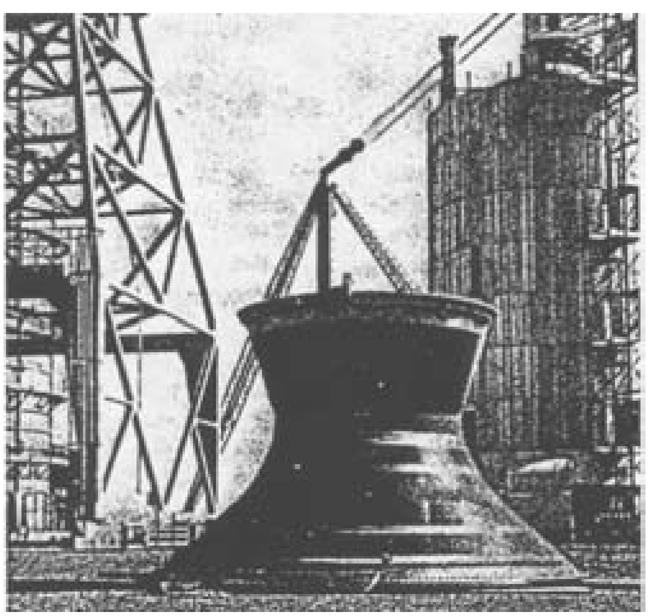


Fig. 30–First all-welded 260 in. diam rocket motor nozzle shell

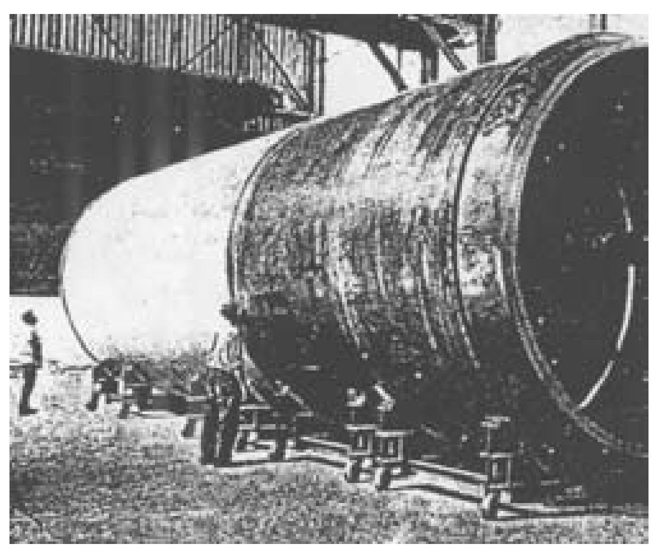


Fig. 31–Two sections of 156 in. diam rocket motor case after fabrication by rolling and welding 18% nickel maraging steel

between the two lies in the fact that plasma-arc uses a nozzle to constrict and shape the DCSP arc in order to concentrate it on a relatively small area.

Gas Metal-Arc Welding

Gas metal-arc welds have usually been made by the common spray-arc technique, but the use of short-circuiting transfer, "narrow-gap with spray transfer," and to a very limited degree, "pulsed spray-arc transfer" have also been examined. Short-circuiting transfer MIG is well established so that differences between it and the standard spray-arc technique need not be repeated here, but the other two modifications; i.e., "narrow-gap" and "pulsed spray-arc" deserve a brief comment.

"*Narrow Gap*".[65,66] This process, developed at Battelle Memorial Institute, employs a normal spray-arc in conjunction with a square-butt, narrow-gap groove. A filler wire, and sometimes two in tandem, are guided into the bottom of the joint by specially designed contact tips. The advantages claimed for the process are, of course, the simple joint preparation (a ¼ - 5/16 in. gap between square butts is suitable for any plate thickness), high deposition rate, and an ability to be used in any position. Use of this process to weld maraging steels has been very limited.

"Pulsed Spray-Arc".[40, 67] With this process, spray transfer is extended to current levels considerably below those required for continuous spray transfer. This is accomplished by using a low "background" power; i.e., one which would produce globular transfer under normal conditions, and superimposing on this a 30 or 60 cps pulse of power (during positive half cycles) which is in the spray-transfer current range. Spray transfer thus occurs by pulsing the power between globular and spray transfer ranges at a rate of 30 or 60 times per second. The advantages of the process are considered to be the higher ratio of heat input to metal deposition in the low current range, and the ability to use spray transfer in this same range. Only a few welds are known to have been made in maraging steels by this new technique.

Welding Procedures

Weld Preparation. Most of the joint designs that have been used for welding these materials by the common inert-gas techniques are fairly standard as shown in Fig. 32. Special configurations, such as those incorporating self-aligning features,[40] are less frequently encountered. Both the vee groove and the U groove designs provide satisfactory results, and while the former are less expensive to prepare, the latter have been extensively used and are sometimes preferred to minimize base-metal dilution of the deposit.

Process Parameters

Some process parameters which have been used for the gas tungsten-arc technique are shown in Table 3. These are by no means the only ones that have been explored or successfully employed, but merely show the range of thicknesses, joint geometries, and conditions that have generally proved satisfactory. In connection with this tabulation, it is pertinent to note that, in line with the basic considerations previously mentioned, neither preheat nor postheat are used, interpass temperatures are restricted, and calculations of heat input (at least for the relatively low speeds normally employed) show that values are low, ranging from less than 5000 joules/in. for a single pass weld in 0.080 in. sheet to about 30,000 joules/in. for multipass welds in 1 in. plate.

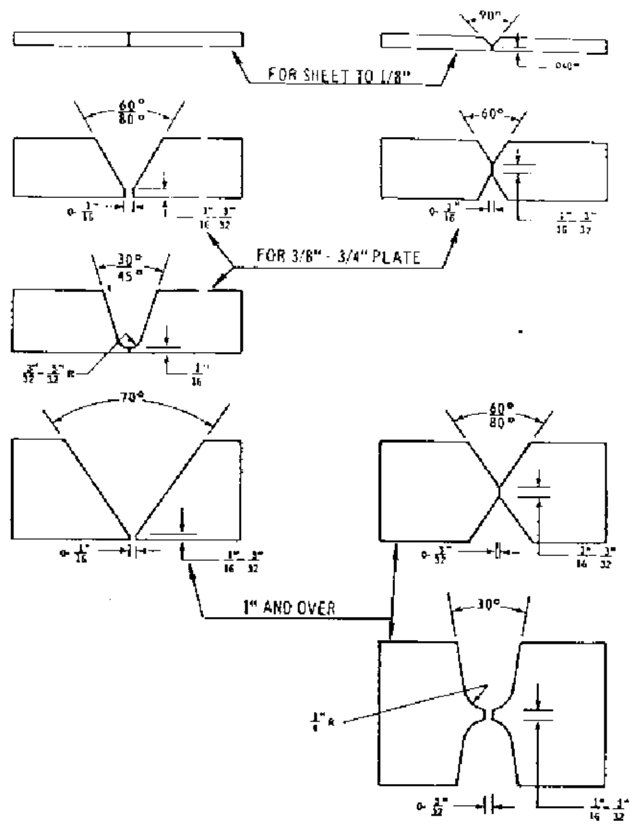


Fig. 32–Some typical joint designs for welding maraging steel

Welding parameters for a variety of gas metal-arc welding techniques are shown in Table 4. Generally speaking, these are known to have yielded sound joints with acceptable properties, but those listed for ac spray-arc and pulsed spray-arc, while probably representative, are based on very limited data.

Like the gas tungsten-arc welds, the gas metal-arc welds are also made without preheat or postheat and with interpass temperatures maintained below about 250° F, but there are several obvious and expected differences between the two processes. The major difference is that the basic spray-transfer gas metal-arc welding process provides considerably higher deposition rates than gas tungsten-arc welding, but at commensurately increased heat inputs. In comparison, both the short-circuiting transfer, and pulsed spray-arc transfer techniques employ heat inputs and deposition rates more comparable in gas tungsten-arc welds. In addition to heat input differences, shielding

Table 3-Some Typical Parameters Used for Gas Tungsten-Arc Welding Techniques[a]

Material thickness, in.	*Joint design*	*No. of passes*	*Volts*	*Amperes, dcsp ,*	*Travel speed, ipm*	*Wire feed, ipm*	*Shiflding gas and flow rate*	*Comments*
0.080	Square butt	1	8	150	7	10	35 cfh argon at cup 10 cfh argon backing	GTA-cold wire feed
0.080	Single V, 90 deg included angle, 0.040 in. land	2	8	120,1st pass 150,2nd pass	11	None 1st pass 10,2nd pass	35 cfh argon at cup 10 cfh argon backing	GTA-cold wire feed
½	Single U, 30 deg included angle, 0.093 in. root radius, 1/16 in. root land	12	9-10	100,1st pass 150,2nd pass 200,passes 3-5 225,passes 6-12	8	l0,passes 1 and 2 20,passes 3-6 30,balance	40 cfh helium + 10 cfh argon at cup 15 cfh argon backup	GTA-cold wire feed
1	Double V,60 deg included angle, 1/16 in. root land, no gap	25-30	10-12	210-230	4-6	20-24	40 cfh argon at cup 10 cfh argon backup	GTA-cold wire feed
¾	Double U,60 deg included angle, 0.093 in. root radius, 0.060 in. root land	8-10	10	340-400	12-15	60-70	40 cfh argon at cup 10 cfh argon backup	"Big TIG" ¼ in. diam electrode
0.6	Single U,60 deg included angle, 0.156 in. root radius, 0.060 in. root land	6	11-11.5 + 5. 5-6.0 for hot wire	265,lst pass 400,balance + 135-170 for hot wire	9,1st pass 14,balance	5.5 lb/hr 8.5 lb/hr	75% helium + 25% argon 100 cfh at cup 25 cfh backup	GTA "hot wire"
0.6	Single V,75 deg included angle, ¼ in. root land, no root gap	4	30,1st pass 35,balance	320,1st pass 310,balance	4.5,lst pass 14,balance	None,1st pass 7 lb/hr on balance	100 cfh,75% helium +25% argon 150 cfh,75% helium +25% argon	Plasma-arc 1st pass GTA "hot wire" fill passes

[a]No preheat or postweld heat used. Interpass temperature maintained below 200° F, 0.062 in. wire.

Table 4-Parameters Used for Gds Metal-Arc Welding[a]

Material thickness, in.	*Joint design*	*No. of passes*	*volts*	*Amperes, dcrp*	*Travel speed, ipm*	*Wire size, in.*	*Wire rate, ipm*	*Shielding gas and flow rate, cfh*	*Comments*
½	Single V,60 to 80 deg included angle, $^1/_{16}$ in. root land and root gap	3-5 3-5	30-34 19-21	290--310 300-320	10 10-12	0.062 0.062[b]	200-220 200	50 cfh argon at cup 10 cfh argon backup 40 cfh argon at cup 10 cfh argon backup +40 cfh in trailing shield	Gas metal-arc spray transfer Gas metal-arc spray transfer ac
½	As above	18	25	125	~6-8 (Manual)	0.035	325	50 cfh helium at cup 10 cfh argon backup	Gas metal-arc short circuiting transfer
¾	Single U,45 deg included angle, 0.093 in. root land, 0.070 in. root gap	10 Passes 1 & 2(TIG) 3-10	8-10 28	160-175 (dcsp) 350-375	4-6 15-20	0.062 0.062	20 ~240	35 cfh argon 50 cfh argon+2% O_2	Gas tungsten-arc root passes Gas metal-arc spray transfer
1	Double V,80 deg included angle, $^1/_{16}$ in. root land, $^3/_{32}$ in. root gap	8	30-34	290-310	10	0.062	200-220	50 cfh argon at cup 10 cfh argon backup	Gas metal-arc spray transfer
1	Double V,60 deg included angle, $^1/_{16}$ in. root land, $^3/_{32}$ in. root gap	24	20 Background 70 Peak	140 (Avg.)	~6	0.045	~180	40 cfh argon + 0.3% O_2 at cup	Gas metal-arc pulsed-spray transfer

[a] No preheat or postheat used. Interpass temperature maintained to 200º F.
[b] Wise emissively coated.

Table 5–Filler Wire Compositions, %

	Parent alloy to be welded Nominal composition[a]						Filler wire Typical analysis[a]					
Grade	Ni	Co	Mo	Ti	Al	Cr	Ni	Co	Mo	Ti	Al	Cr
18Ni200	18	8.5	3	0.2	0.1	...	18.2	7.7	3.5	0.24	0.10	
18Ni250	18	8	5	0.4	0.1	...	18.1	8.0	4.5	0.46	0.10	...
18Ni300	18	9	5	0.6	0.1	...	17.9	9.9	4.5	0.80	0.12	...
18Ni350	18	12	4	1.6	0.1	...	17.4	12.4	3.7	1.6	0.17	...
12-5-3	12	...	3	0.2	0.3	5	12.1	...	3.1	0.30	0.30	5.0
12-5-3	12	...	3	0.2	0.3	5	17.0	2	3.0	0.40	0.10	...

[a] Balance essentially iron-residual elements normally kept to maximum values shown below, but as low as practical:

Weight Percent						ppm		
C	S	P	Si	Mn	B Zr	O	N	H
0.03	0.01	0.01	0.10	0.10	Not added	<50	<50	<5

Table 6-Effects of Alloying Elements on 18% Nickel Maraging Steel

Element	*Amount present*	*Effects in parent material*	*Effects in welds*
Nickel	Too low	Lowers strength.	Lowers strength and resistance to cracking.
	Too high	Promotes austenite, lowering strength and toughness.	Segregated austenite pools reduce both strength and toughness.
Cobalt and molybdenum	Too low	Lowers strength.	Lowers strength.
	Too high	Increases strength up to a point, but lowers notch properties, and at excessive levels, reduces strength as well.	Similar to parent metal.
Titanium	Too low	Lowers strength.	Lowers strength, and increases tendency to porosity.
	Too high	Lowers notch properties.	Promotes stable austenite which lowers strength, forms inclusions with carbon and/or nitrogen, forms low melting point sulfides.

for the gas metal-arc process can employ small additions of oxygen for arc stabilization, and short-circuiting transfer welding entails the use of helium (though both helium-argon and helium-argon-CO_2 mixtures have also been used).

Filler Wire Selection

The effects of wire chemistry on joint soundness and properties have been studied extensively for the 18Ni (200), 18Ni (250)[28,30,39,51,68,69] and 12-5-3[50,54,57] alloys, and compositions closely matching those of the parent metal are now well established. Less work has been done with the 18Ni (300) or (350) grades.[70]

Table 5 compares typical wire analyses with the nominal compositions of the plates they are used to weld.

Weld-metal strength can be varied widely by adjusting the hardener content of the wire, but as strength is increased, both ductility and toughness are sacrificed. Furthermore, the richer the alloy the more prone it is to segregation, and during aging, the alloy-rich areas may revert to pools of stable austenite, Figs. 33 and 34. Although these are tough, they are low in strength, and can act as points of initiation for fracture. A summary of the effects of the major alloying elements in maraging steels is given in Table 6.

Residual elements also have important detrimental effects as shown in Table 7, and are normally kept as low as possible. Carbon and sulfur are particularly undesirable; carbon, because it forms embrittling inclusions and ties up the hardeners, thus reducing strength, and sulfur because it forms low-melting sulfides that increase crack susceptibility and lower notch properties. The effect of co-present sulfur and silicon on the toughness of welds in 12-5-3 is shown in Fig. 35. Similar effects would be expected in 18% nickel welds.

Table 7-The Role of Residual Elements in Maraging Steel

Element	*Effects*
Carbon	Ties up titanium and molybdenum to reduce strength. Ti carbide inclusions can harm ductility and notch properties.
Sulfur	Particularly in welds, low melting point titanium sulfides promote hot shortness, and reduce ductility and toughness.
Silicon	Lowers impact properties and increases weld crack sensitivity.
Manganese	Lowers impact properties.
Aluminum	Increases strength at the expense of ductility and toughness.
Boron and zirconium	Improves toughness of plate, but increases crack sensitivity and reduces toughness in welds.
Hydrogen	Welds with more than about 3 ppm may be crack sensitive.
Oxygen and nitrogen	Form oxides or nitrides which damage ductility and toughness.

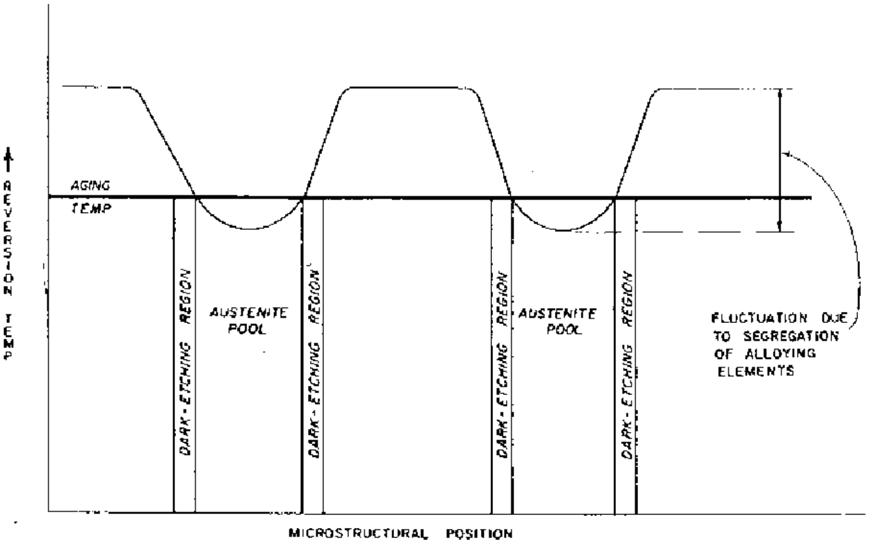


Fig. 33–Schematic illustration of austenite pool formation

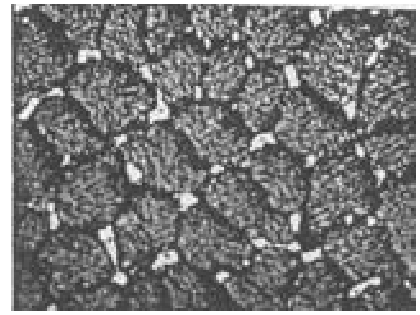


Fig. 34–The microstructure of a gas metal-arc weld made with the standard 18Ni (250) filler showing inclusions in the austenite pools. Etchant: modified Fry's Reagent. X750 (Reduced 40%)

Mechanical Properties

Typical examples of property levels attained in gas tungsten-arc and gas metal-arc weldments are shown in Tables 8 and 9, respectively. The data are representative, but since a variety of welding techniques, heat treatments, and heats of both parent metal and filler are involved, direct comparisons of specific properties would not be appropriate.

Tensile Properties

Welds in those alloys having nominal yield strengths up to about 250 ksi are typified by strengths close to those of the parent alloy being welded. Joint efficiencies of 95-100% are usual, but welds made with high heat inputs can have efficiencies down to 85% and occasionally even lower. The tensile failures in such welds often occur in the heat-affected zone as the result of formation of relatively large volumes of stable austenite.

As parent alloy strength is raised above 250 ksi to 300 or even 350 ksi, joint efficiencies decrease. Small beads and low heat inputs help keep strength reductions to a minimum. Solution annealing a weld prior to aging can increase strength significantly (Table 10), but this may often be impractical.[71]

Tensile ductility is usually high, but both elongation and reduction of area values for gas metal-arc welds are frequently lower than for similar gas tungsten-arc welds. These differences are larger and more noticeable in the higher strength alloys. Both the greater number of inclusions normally present in the gas metal-arc welds, and their coarser, less refined, structure are likely reasons for this behavior.

Weld Metal Toughness

The toughness (Figs. 36 and 37) of gas tungsten-arc welds tends to match the toughness of the parent alloy. Gas metal-arc deposits made by either spray or short-circuiting techniques are somewhat poorer, and the data shown in Fig. 36 show this difference clearly. It is interesting to note that, since all these welds were produced with a single heat of 18Ni (250) filler, one would normally expect that, for a given process, deposit toughness should vary little from plate to plate. The data fail to confirm this. Gas tungsten-arc welds exhibited higher toughness in 200 than 250 ksi plate, whereas the toughness of gas metal-arc welds was lower in the 200 ksi plate than in the 250 ksi material. If the improvements shown by

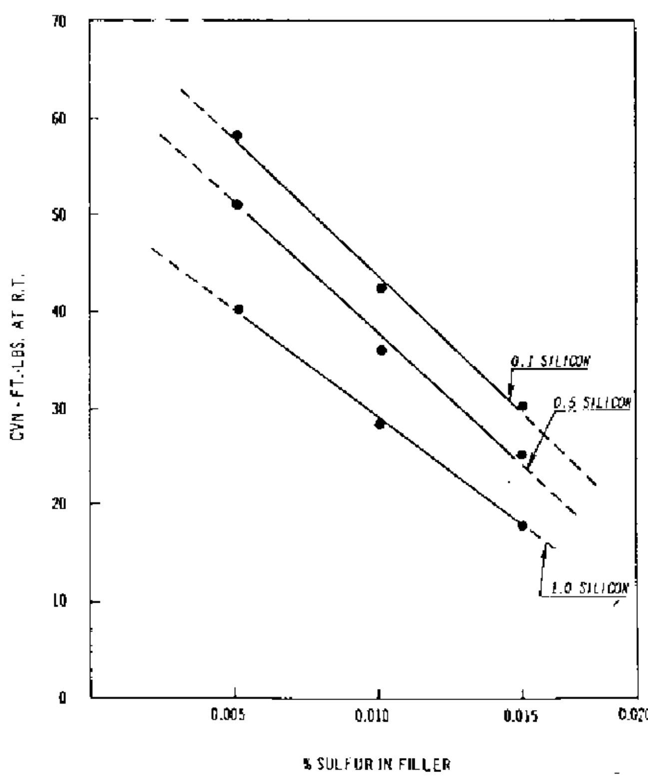


Fig. 35–The effect of filler wire silicon and sulfur contents on the toughness of 180 ksi Y.S. manual G.T.A. welds in 12-5-3 maraging steel

Table 8-Room Temperature Properties of Automatic Gas Tungsten-Arc Welds[a]

Material grade	*Thick-ness[b]*	*Filler type[c]*	*0.2% Y.S., ksi*	*U.T.S., ksi*	*% Elong., in 1 in.*	*R.A., %*	*Approximate efficiency, % (based on Y.S.)*	*Toughness CVN, ft-lb*	*Toughness K_{Ic}, ksi √in.*
18Ni (200)	Plate	18Ni (200)	206-212	213-215	12	58-60	95	...	98-111
18Ni (200)	Plate	18Ni (200)	203-205	208-210	10-12	57-59	95	...	90-101
18Ni (200)	Plate	18Ni(200)	208-212	213-214	11-12	53-58	95	...	…
18Ni (200)	Plate	18Ni(200)	212-214	217	11-12	54	100	...	130
18Ni (200)	Plate	18Ni (200)	199	207[e]	13	59	90	35-37	...
18Ni (250)	Plate	18Ni (250)	225-235	235-243	10-11	44-47	95	...	...
18Ni (250)	Plate	18Ni (250)	237	242	6 (in 2 in.)	32	95	11	62-63
18Ni (250)	Plate	18Ni (250)	220	227	13	60	90	19-23	
18Ni (300)	Plate	18Ni (300)	202	243	8	40	75	...	59
18Ni (300)	Sheet	18Ni (300)	261-280	265-285	…	...	84-90	...	113-162 (K_c)
18Ni (300)	Sheet	18Ni (300)	239	242	3 (in 2 in.)	...	84	...	. . .
18Ni (350)	Sheet	18Ni (350)	285	294	1. 5 (in 2 in.)	...	77	...	33
12-5-3	Plate	12-5-3	176	182	15	65	95	66-79	...
12-5-3	Plate	12-5-3	179	192	14	58	95	45	...
12-5-3	Plate	17-2-3	178	186	13	63	95	54	...
12-5-3	Plate	17-2-3	174-179	183-187	14-15	55-56	95	47-52	...
	Process[d]								
18Ni (250)	"Big TIG"	18Ni (250)	243	244	12-16	21-28	97	...	70-80
18Ni (200)	"Hot wire"	18Ni (200)	201-203	208-211	12	46-48	95	...	132-148
18Ni (200)	"Hot wire"	18Ni (200)	186-195	197-205	9-13	43-58	90	...	...
18Ni (200)	"Plasma"	18Ni (200)	207	214	12	55	95	...	117
12-5-3	"Hot wire"	12-5-3	168-169	170-172	12	55-57	90	42-59	...

a After aging at 900° F 3-10 hr; tensile properties from transverse specimens; all welds cold-wire feed unless noted.
b Plate = 0.4-1.0 in. sheet = 0.060-0.100 in.
c See Table 3 for typical composition.
d All welds in plate thickness.
e Heat-affected zone failure-manually welded.

Table 9-Room Temperature Properties of Automatic Gas Metal-Arc Welds[a]

Material grade	*Thick-ness[b]*	*Filler type[c]*	*0.2% Y.S., ksi*	*U.T.S., ksi*	*% Elong., in 1 in.*	*R.A., %*	*Approximate efficiency, % (based on Y.S.)*	*Toughness CVN, ft-lb*	*Toughness K_{Ic}, ksi √in.*
18Ni (200)	Plate	18Ni (200)	213-217	214-220	11	56	100	...	76
18Ni (200)	Plate	18Ni (200)	197-201	205-208	...	...	90,	17-18	...
18Ni (200)	Plate	18Ni (200)	208	214	6	34	95	18-22	...
18Ni (250)	Plate	18Ni (250)	220	235	7	. .	90	13	...
18Ni (250)	Plate	18Ni (250)	225-247	230-252	1.5-6.0	13-37	83-91	...	...
18Ni (250)	Plate	18Ni (250)	238-243	247-252	2.8-5.5	18-38	95	...	...
18Ni (250)	Plate	18Ni (250)	226	243	4	7	90	7-10	...
18Ni (250)	Plate	18Ni (250)	...	...	...	...	...	...	70-80
18Ni (300)	Plate	18Ni (300)	232	245	3	13	85	...	54
12-5-3	Plate	12-5-3	176-187	182-191	10-12	47-58	90-95	34-50	...
	Process[d]								
18Ni (200)	"Pulsed-arc"	18Ni (200)	203	208	5.3	...	100	24	...
18Ni (250)	"Short-arc"	18Ni (250)	228	245	4	14	95	12	...
18Ni (250)	"Short-arc"	18Ni (250)	...	...	...	...	...	...	65-75
12-5-3	"Pulsed-arc"	12-5-3	180	188	9	32	95	30	...

[a] After aging at 900° F for 3-10 hr; tensile properties from transverse specimens; all welds spray-arc unless noted.
[b] Plate = 0.4-1.0 in.
[c] See Table 3 for typical composition.
[d] All welds in plate thickness.

the gas tungsten-arc welds are attributed to dilution effects, then the contrasting behavior of the gas metal-arc welds (in spite of similar or greater dilution) suggests a strong effect of the process itself. It appears that, like tensile ductility, the toughness of gas metal-arc welds is governed to a large extent by their somewhat poorer cleanliness (Figs. 38 and 39). The coarser structure of these deposits is probably also a factor.

The fracture surfaces of gas tungsten-arc welds show elongated dimples with small inclusions visible at the bottom of them. This is typical of fracture surfaces of maraging steels; the fracture surfaces of base plate samples look the same. The fracture surface of the gas metal-arc welded sample has more inclusions than the gas tungsten-arc weld, but the characteristic dimples are still very evident.

Like all high-strength alloys, deposit toughness

Table 10-The Effects of Postweld Annealing on the Properties of Experimental High-Strength Maraging Steel Weld Metals

0.2% Y.S. of parent metal, ksi	*Nominal filler wire composition, %*						*Weld properties: Aged 800° F/24 hr*			*Weld properties: Annealed 1500.° F/1 hr + aged 800° F/24 hr*		
	Ni	*Co*	*Mo*	*Al*	*Ti*	*Other*	*0.2% Y.S., ksi*	*U.T.S., ksi*	*CVN, ft-lb*	*0.2% Y.S., ksi*	*U.T.S., ksi*	*CVN, ft-lb*
Gas Tungsten-Arc Welds[a]												
265	18	15	3	0.1	Nil	0.5V	218	222	12[b]	260	269	12
265	18	15	3	0.1	0.3	...	223	236	22[b]	253	265	...
265	18	9	2	0.1	0.7	2.9W + 0.5V	228	239	15[b]	250	262	16
275	18	16	3	0.1	0.1	0.5V	211	225	16[b]	263	272	19
275	18	16	3	0.1	0.2	0.5V	208	223	13[b]	267	277	17
275	18	13	4	0.1	0.3	0.5V	227	244	15[b]	268	279	15
275	18	13	4	0.1	0.3	0.5V	229	246	12[b]	270	285	14
275	18	15	3	0.1	0.3	2.8W	241	252	13[b]	299	307	11
275[c]	18	16	3	0.1	0.2	...	250	255	15	266	274	20
Gas Metal-Arc Welds[d]												
275	18	16	3	0.1	0.2	...	252	261	9	267	272	12
290	18	15	3	0.1	0.2	...	251	262	9	266	272	10
290	18	15	3	0.1	0.2	2.9W	270	276	5	290	298	6

a Manual welds unless otherwise specified. Heat input approximately *72,000* joules/in.
b Tensile failure in heat-affected zone. All other failures in weld metal.
c Automatic weld-heat input *16,500* joules/in.
d Automatic welds-heat input *54,000* joules/in.

decreases with decreasing temperature as shown in Fig. 40 for gas tungsten-arc welds in 12-5-3.

Effects of Heat Treatment on Weld Properties

Table 11 shows that variations in aging temperature between 850 and 925° F and for times between about 3 and 12 hr result in only minimal property changes in the materials shown. Any increases or decreases in strength are accompanied by corresponding, but inverse, changes in toughness.

Annealing prior to aging tends to raise strength and has an even more pronounced effect when used in conjunction with a high-temperature homogenization, (see the 250 ksi alloy in Table 11). Such a homogenization treatment of course is not only impractical, but promotes base-metal grain coarsening and possible embrittlement.

Defects and Their Control

Cracking, both in the weld metal and in the heat-affected zone, has been observed, but only rarely,[58,69] and gas tungsten-arc welds have been particularly crack-free. Deposit cracking has been observed in interpass areas in association with inclusions, probably oxides. The nature of the cracking observed suggests that careful control of all the factors affecting joint cleanliness should assure continued freedom from such defects.

Porosity has been more frequent and troublesome in both gas tungsten-arc and gas metal-arc welds. Gas tungsten-arc weld porosity has invariably been associated with unclean wire, inadequate cleaning during preweld preparation, or during interpass wire brushing or grinding. As previously mentioned,

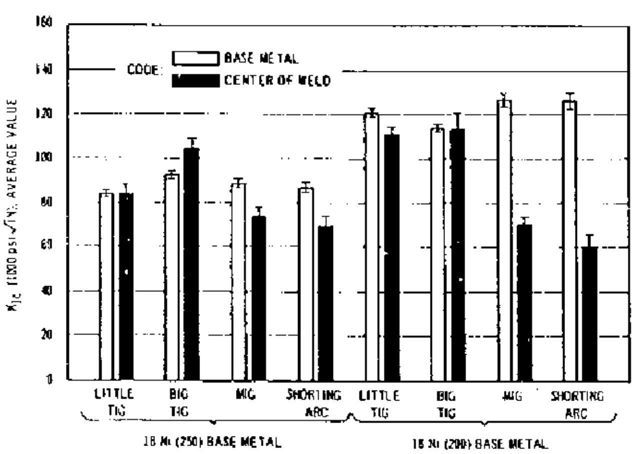


Fig. 36–Comparative toughness of welds and base metal in *250* and *200* grades of *18Ni* maraging steel. Test bars parallel to plate rolling direction

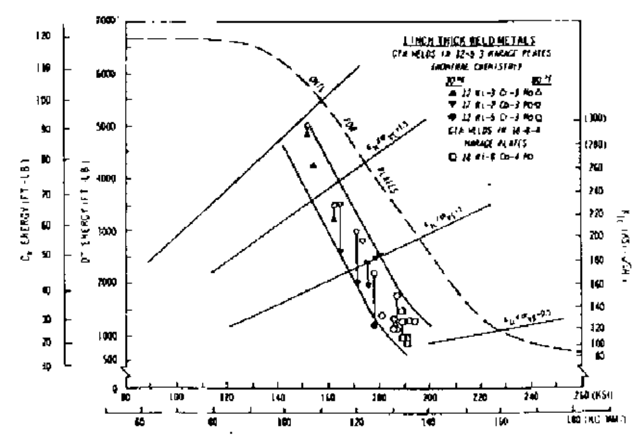


Fig. 37–Ratio analysis diagram (RAD) trend band for maraging welds compared to plate material limit properties as defined by optimum material trend line (OMTL)

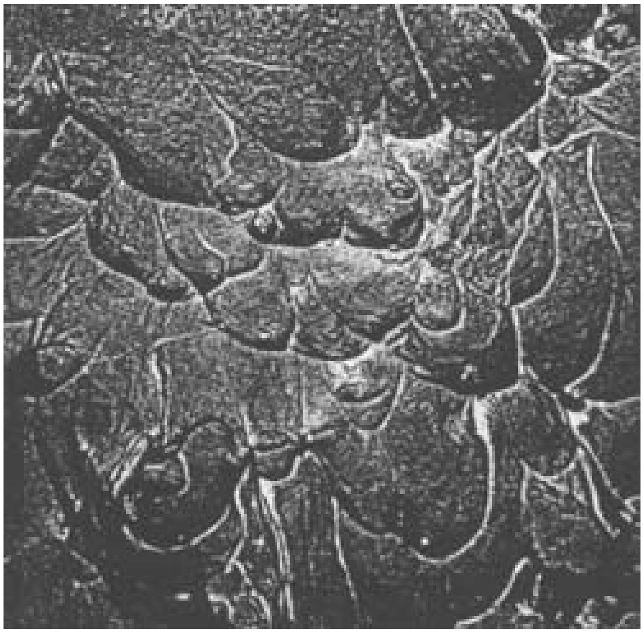


Fig. 38–Electron micrograph of fracture surface of gas tungsten-arc weld in 18Ni (250) showing elongated dimples with small inclusions visible at their bases. X7500 (Reduced 55%)

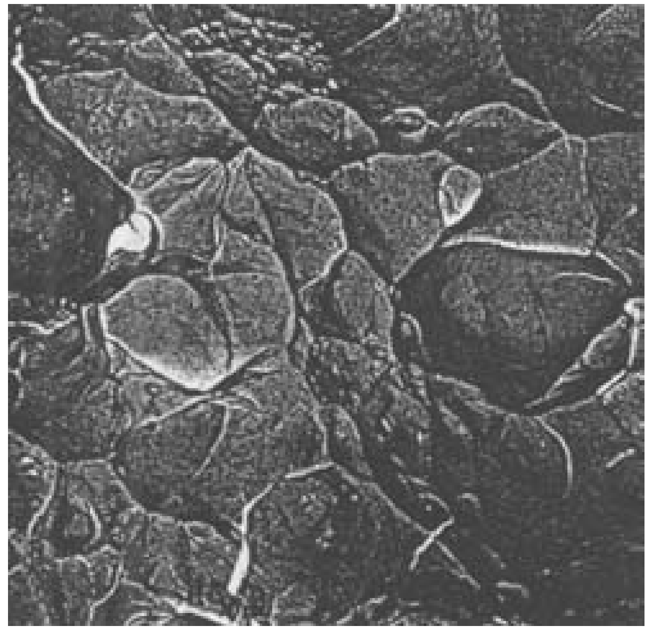


Fig. 39–Electron micrograph of fracture surface of gas metal-arc weld in 18Ni (250) showing dimpled facets with inclusions. Compare to gas tungsten-arc weld in Fig. 38. X7500 (Reduced 55%)

meticulous control of wire and joint cleanliness has been successful in minimizing the occurrence of porosity in these welds.

The incidence of porosity in gas metal-arc welds has been much higher,[21, 51, 69] and considerable effort has been expended to investigate the effects of important welding variables (including joint design, welding conditions, shielding methods, and shielding gas) in reducing the problem. Shielding has been found to be the most important variable, and the use of small nozzles to reduce the distance between the cup and the work was found to be quite effective in reducing the number and size of pores. Increased welding speeds; i.e., above about 10-12 ipm promote a tendency to porosity unless a trailing shield is employed. This difficulty is related to

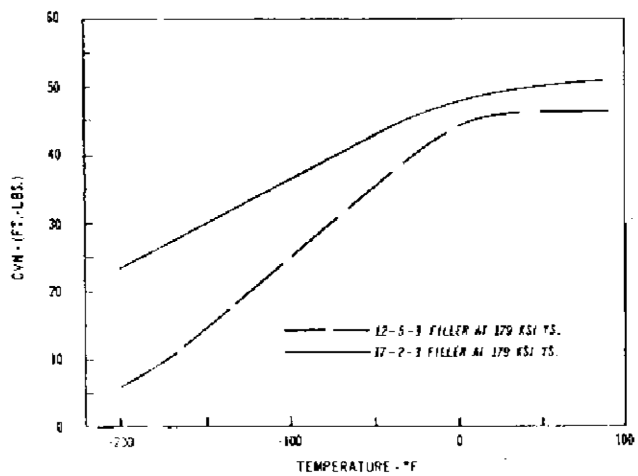


Fig. 40–Toughness vs. temperature for gas tungsten-arc welds in 12-5-3 maraging steel

Table 11-Typical Effects of Postweld Heat Treatment on Weldment Properties[a]

Grade	*Welding process*	*Filler wire*	*Postweld treatment*	*0.2% Y.S., ksi*	*U.T.S., ksi*	*Elong., % (in I in.)*	*R.A., %*	*Toughness CVN, ft-lb*	*Toughness K_{Ic}, ksi √in.*
18Ni (200)	GTA	18Ni (200)	850º F/8 hr	213	217	11	56	...	101
			900º F/4 hr	214	219	11	53	...	105
			900º F/8 hr	220	225	13	52	...	101
			950º F/8 hr	210	220	12	52	...	110
18Ni (250)	GMA	18Ni (250)	900º F/3 hr	241	243	6	21	...	...
			1500º F/1 hr + 900º F/3 hr	242	257	7	26	...	...
			2100º F/1 hr -i-. 1500º F/1 hr + 900º F/3 hr	274	283	8	38	...	
12-5-3	GTA	12-5-3	As-welded	127	141	15	70	94-105	...
			900º F/6 hr	179	182	14	64	62- 64	...
			850º F/12 hr	181	184	13	61	56- 60	...
12-5-3	GMA	12-5-3	As-welded	129	140	12	68	71- 78	...
			900º F/6 hr	176	182	12	57	45- 46	...
			850º F/12	179	184	12	58	38- 41	...

[a] All welds in plate thickness.

incomplete removal of the tenacious, black scale that forms when shielding is inadequate. The fact that oxygen additions increase scaling and promote porosity tends to confirm this. Porosity decreases with increasing heat input,[21] but in light of the poorer weld properties that usually accompany high heat input, this does not appear to be a practical solution.

Lack of fusion has been observed in short-circuiting gas metal-arc welds, but is a normal tendency of this generally "cold process," and can be avoided by careful control of heat input, and welding techniques, and by meticulous interpass cleaning.

VI. Welding with the Flux-Shielded Processes

General Considerations

The shielded metal-arc, submerged-arc, and electroslag processes have all been successfully employed to weld the maraging steels, but their use has been limited. This is a result of the interrelated facts that: (1) most of the applications for these alloys have demanded high integrity and good joint properties, and (2) neither the materials nor techniques needed to meet these requirements consistently have been adequately developed for these processes.

There has been no real difficulty in achieving welds of the required strength, but they have been associated with a greater propensity to weld cracking and poorer toughness than has been observed in joints made by inert-gas welding. A major reason for these differences appears to be in the basic dissimilarity between the two types of shielding employed. Inert-gas shielding is basically just that, whereas welding fluxes appear to be neither non-reactive nor of high purity.

Shielded Metal-Arc Welding

Filler Materials. Electrodes for welding the 200 and 250 ksi grades of the 18% nickel alloys have been developed,[39,72] but have not been produced commercially to any great extent. The rods are composed of 18Ni - Co - Mo core wires coated with basic lime-cryolite or lime-titania fluxes, and deposit metal of composition closely matching that of the parent alloy (Table 12).

Table 12-Shielded Metal-Arc Core Wire and Deposit Analysis, %

	18% Ni–250	*Grade*	*18% Ni-200*	*Grade*
	Core wire	*Deposit*	*Core wire*	*Deposit*
Iron	Balance	Balance	Balance	Balance
Nickel	18.0	18.7	18.0	18.30
Cobalt	8.0	7.35	7.65	7.80
Molybdenum	4.5	4.50	2.20	2.30
Titanium	2.2	0.46	2.32	0.57
Aluminum	0.15	NA[a]	0.15	NA
Carbon	<0.03	0.02	0.019	NA
Manganese	<0.05	NA	<0.10	NA
Silicon	<0.05	0.19	<0.10	NA
Sulfur	<0.01	NA	<0.01	NA
Phosphorus	<0.01	NA	<0.01	NA
Boron	None added	NA	None added	NA
Zirconium	None added	NA	None added	NA

[a] NA = not analyzed.

Core wire compositions are basically the same as the parent alloy but the titanium contents are increased to assure freedom from weld cracking[39] and porosity, and to make up for the high losses of this hardening element across the arc. A variety of flux compositions have been evaluated, but those recommended to date are of the silicate-bonded lime-cryolite or lime-titania types. Silica in the flux is kept low to minimize silicon pickup in the weld.

Welding Techniques. Standard joint geometries can be used; e.g., butt welds have been made in ½ in. material using single Vee 60 deg included angle with a 1/16 in. root land and a 1/16 to 3/32 in. root opening, while single or double U-grooves with ¼ in. root radius and 15 deg side walls have been used for heavier material. Though both ac and dcrp have been employed, the latter is preferred, undoubtedly because the flux coatings were not formulated specifically for ac or ac-dc operation. Welding currents in the range 115-130 amp and 130-145 amp have proved satisfactory with 5/32 and 3/16 in. electrodes, respectively. Neither preheat nor postheat are necessary, and an interpass temperature of about 250° F maximum is usually suggested. The extent of interpass cleaning required depends upon bead contour and slag make-up, but the rather basic fluxes that have been used yield a friable, easily removed slag. Stainless power wire brushing is normally sufficient for final bead clean up.

Mechanical Properties and Heat Treatment. The properties of typical ½ in. shielded metal-arc butt welds are shown in Tables 13 and 14. In the fully aged condition weld strengths are generally equal to or better than that of the parent plate as indicated by parent metal failures. Under-aging at approximately 700° F results in low weld strength and there is no benefit to deposit toughness. In the as-welded condition, or after low temperature (300 to 500° F) aging, weld strength is comparatively low, 140 ksi yield, but deposits have considerable toughness. Typical deposit hardness before and after aging are shown in Fig. 41.

Defects and Their Control. Welding defects have not been a serious problem. Both porosity and slag entrapment were found during the early stages of development, but the high titanium level of the core wire cured the former problem, and the latter was eliminated by flux modification.

Neither weld nor heat-affected zone cracking was observed in 3/16 in. tee-fillet welds or butt welds to 1 in. when the optimum electrodes were employed; but Witherell[39] found that transverse hydrogen-induced cold cracking of weld metal occurred when low-nickel (14-16%) core wires were used. These defects, often undetected by X-ray, occurred in the reheated region of previously deposited beads, and were only found on subsequent destructive examination. While such defects are less likely to occur when the proper-low-hydrogen rods are used, it is desirable to employ small weld beads and extended interpass delays.

Table 13-Properties of ½ in. Shielded Metal-Arc Butt Welds

			Room temperature properties[b]						
Plate type	*Core Wire*[a]	*Flux type*	*0.2% Y.S., ksi*	*U.T.S., ksi*	*N.T.S., hsi*	*% Elong. (in 1 in.)*	*R.A., %*	*Location of failure*	*CVN, ft-Ib*
18/250	1	Lime-cryolite	226.3	235.2	276.3	5	20	Weld	_ _
18/200	2	Lime-cryolite	209.7	217.8	...	9	15	Weld	14
18/200	3	Lime-cryolite	198.0	210.0	...	12	51	Plate	12
18/200	3	Lime-titania	192.0	198.0	...	11	44	Weld	18

[a] Core wire composition, % (balance essentially iron):

	Ni	Co	Mo	Ti
1	18.0	8.0	4.5	2.2
2	18.0	7.65	2.2	2.3
3	18.0	1.1	3.5	2.6

[b] After aging for 3 hr at 900° F.

Table 14-Effects of Heat Treatment on the Mechanical Properties of Shielded Metal-Arc Butt Welds in 200 ksi Yield Strength Plate[a]

Postweld heat treatment							
Time, hr	Temp., °F	Weld metal hardness (Rc)	0.2% Y.S., ksi	U.T.S., hsi	% Elong. (in 1 in.)	R.A., %	CVN, ft-lb
As-welded		37	142.2	157.6	3	7	31
1	300	38	140.2	158.4	3	9	34
1	500	38	145.3	163.6	10	33	30
1	700	41	164.5	181.8	12	43	17
1	800	46	181.6	194.8	10	34	15
1	900	42	197.4	206.0	10	39	18
3	900	47	209.7	217.8	9	15	14

[a] Core wire No. 2, Table 13.

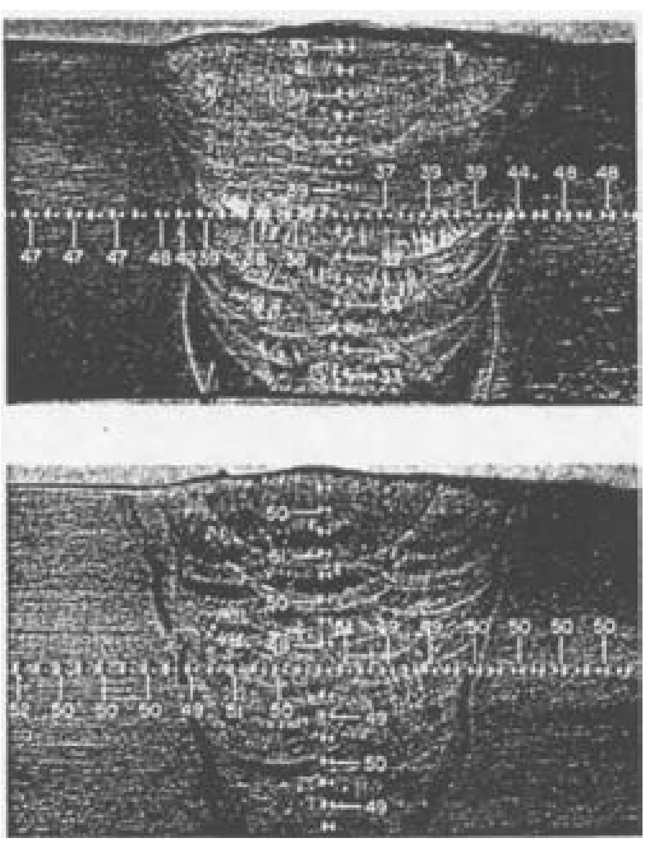


Fig. 41–Cross-section of 1 in. thick covered electrode butt weld in maraged plate showing hardness in the as-welded condition (top) and after a 3 hr maraging heat treatment at 900° F (bottom). Hardness values shown are Rockwell "C"

Submerged-Arc Welding

Filler Wires. Virtually all submerged-arc welding of the maraging steels has been on the 18Ni (250) grade, and filler wires matching the composition of parent metal, except for increased titanium contents, have been used.

The increased titanium contents stem from the original work of Witherell, et a1.[39,43] in which it was shown that this was necessary in both shielded metal-arc and submerged-arc welding to obtain thorough weld-metal deoxidation. Since that time, wires containing between nil and about 2.5% titanium have been investigated[41,59,69,73,74] but none of these studies has been sufficiently comprehensive to permit definition of a "recommended" titanium level. Recovery in the deposit ranges from about 30-70% depending on flux composition and welding parameters, but it appears that the loss can be held reproducibly to about 50%.[41] About 0.30-0.40%, titanium in the deposit is necessary to provide strength equivalent to that of 18Ni (250) parent plate.[69] Since greater amounts reduce weld toughness and promote cracking due to the formation of titanium-bearing inclusions,[58] it appears that a level of 0.60-0.80% in the filler should be adequate but not excessive.

Flux Composition. Early submerged-arc welding tests showed that commercially available flux compositions (typified by the analysis shown in Table 15) were not satisfactory because they produced crack sensitive, brittle welds and did not provide depend-

Table 15-Analyses of Submerged-Arc Welding Fluxes, %

Flux component	*Fused commercial flux*	*Agglomerated experimental fluxes* *No. 1*	*No. 2*	*No. 3*	*No. 4*	*No. 5*
SiO_2	39.72					
MnO	35.81					
CaO	13.10					
MgO	1.45			13.5	12.5	13.3
TiO_2	0.04					
FeO	0.14					
Fe_2O_3	1.85					
$A1_2O_3$	4.32			36.0	34.0	35.0
K_20	0.96					
Na_20	0.94					
BaO	0.53					
CaF_2		7.0	6.5	13.5	12.5	14.1
$CaCO_3$		16.0	14.5	27.0	25.0	26.4
Bentonite		2.0	2.0			
Zircon sand		17.0	15.0			
CaO -$Si0_2$		55.0	50.0			
FeSi(50/50)		3.0	2.5	1.0	1.0	
FeTi(40%Ti,5%A1,Bal. Fe)			10.0		7.5	5.7
Na_20-3$Si0_2$				9.0	8.0	
Na_20-3SO_2-1 part) K_20-2SiO_2-2 parts)						5.5
Typical weld Ti content[a]		0.07	0.49	0.40	0.44	0.50
		0.10-0.20	0.80	0.86	0.78	0.95
Typical weld Si content[a]			0.45	0.135	0.20	0.12-0.13
			0.58	0.190	0.24	0.13

[a]*Upper values obtained using a 0.71-0.73% Ti wire; lower values obtained using a 2.23% Ti wire.*

able titanium recoveries. This was attributed in some measure to impurities such as carbon and sulfur, and also to high silica and manganese oxide contents which led to high silicon and manganese pickup in the deposit and loss of titanium. Subsequently, several low-manganese, low-silicon fluxes were developed[75] and while their exact compositions are not generally known, they probably rely heavily on virtually complete elimination of silicon- and manganese-bearing ingredients and substitution of the stable oxides of magnesium, calcium, and aluminum. The published composition developed in at least one case[73] is perhaps representative:

Aluminum oxide	37%
Calcium carbonate	28%
Calcium fluoride	15%
Magnesium oxide	14%
Ferro titanium	6%

The sequential steps in development of this flux are summarized in Table 15 (from Ref. 73) and show how the flux ingredients and the titanium contents of the filler wire determine the titanium and silicon contents in the weld deposit.

Joint Design and Process Parameters. Material up to about 3/8 in. thick has been welded in a single pass using square butt joints. Typical welding conditions were 500 amp dcrp and 27 v, using a welding speed of 10 ipm and feeding 1/8 in. filler. Multipass ½ in. joints have also been made with a 60 deg vee joint and 1/16 in. wire using 230 amp dcrp and 27 v, at travel speeds of 10-18 ipm.[76]

For material between about ¾ and 1¼ in., a variety of joint designs and welding conditions has been attempted,[41,58,59,73] but virtually all successful welding has employed a two-pass procedure using a double-vee or double-J groove geometry and parameters of the type shown in Fig. 42. It has been sug-

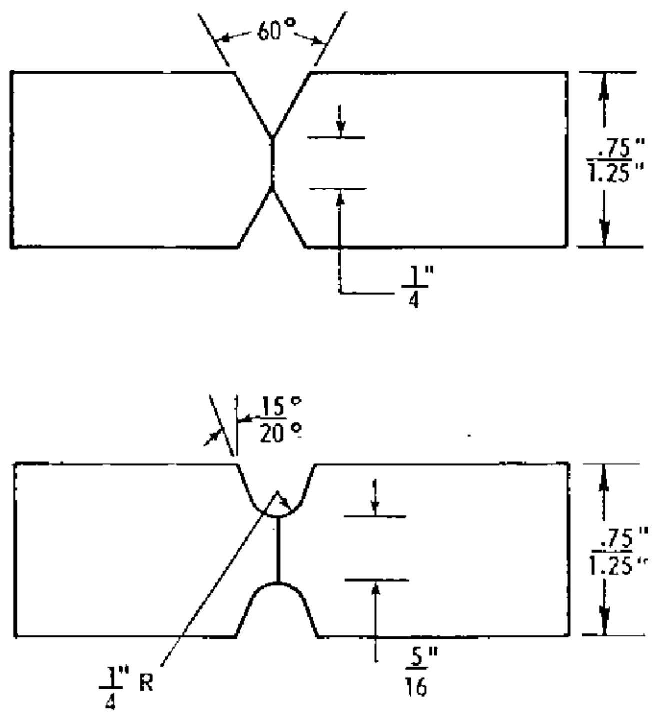


Fig. 42–Joints for two-pass submerged-arc welds. Typical parameters: 500-600 amp. DCRP; *27-30 volts: 10-12 ipm travel; 0.125 in. diameter wire*

Table 16-Typical Transverse Tensile Properties of Submerged-Arc Welds[a]

Joint thickness, in.	*Filler wire*	*0.2% Y.S., ksi*	*U.T.S., ksi*	*% Elong. (in I in.)*	*R.A., %,*	*Location of failure*	*Aging treatment*
1	b	240	241	1.0	15	Weld	900° F/3 hr
1	b	231	252	7.0	33.0	Weld	900° F/3 hr
1	b	251	265	5.0	19.5	Weld	900° F/3 hr
1	b	248	267	6.0	27.5	HAZ	900° F/3 hr
¾	c	232	238	3.0	3.0	Weld	915° F/3 hr
¾	c	207	216	6.0	8.7	Weld	830° F/4 hr

[a] Two-.pass welds made using 3/32= in. 1/8 in. filler, a commercial low silicon, low manganese flux, and a variety, of welding conditions.

	Ni	Co	Mo	Al	Ti	C	S	P	Si	Mn
b	18.1	8.28	4.74	0.25	2.50	0.02	0.003	0.002	<0.01	<0.01
c	18.0	7.88	4.82	0.08	0.65	0.02	0.007	0.002	0.02	0.08

Table 17-Toughness Data for-Submerged-Arc Weldments in 18%, Nickel Maraging Steel

Joint thick-mess, in.	0.2% Y.S., ksi	CVN, ft-lb Range	CVN, ft-lb Average	Fracture toughness (K_{Ic}), ksi √in Range	Fracture toughness (K_{Ic}), ksi √in Average
¾	232[a]	...	...	35.5-42.5	38.0
¾	207[b]	...	…	41.0-56.5	50.8
1	240[c]	5-7	6	...	...
1	231[c]	5-8	7	...	...
1	251[c]	5-9	7	...	...
1	248[c]	4-4	4	...	…

[a] Specimens aged at 915° F/4 hr and air cooled.
[b] Specimens aged at 830° F/4 hr and air cooled.
[c] Specimens aged at 900° F/3 hr and air cooled.

gested that using a non-symmetrical groove to provide a first-pass pool depth of 60-75% of the plate thickness, and employing gas backup to shield the underside of the groove tends to significantly reduce the number of defects that may be encountered. Attempts to produce multipass welds, either in single-J or asymmetrical double-vee grooves using normal submerged-arc practices have resulted in weld cracking.

Mechanical Properties. Little difficulty has been experienced in producing high-strength submerged-arc welds in these materials as indicated in Table 16, but weld ductility and toughness (Table 17) are considerably poorer than are normally achieved in inert-gas welds. The poorer ductility and toughness are probably evidence of the dirtiness and embrittlement previously discussed. The reduced toughness is particularly serious, since it predicts critical flaw lengths of only 1/3 to ½ of those necessary to promote unstable crack propagation in TIG or MIG welds, and there is considerable doubt that such defect sizes can be reliably detected by presently available non-destructive testing techniques.[77]

Defects and Their Control. Weld metal and heat-affected zone cracking have been encountered in submerged-arc weldments. Both hot cracking, and delayed cold cracking have occurred.

Cold Cracking. Transverse cold cracking, starting in the weld metal and sometimes extending into the heat-affected zone, has been observed as much as 24 days after the weld was inspected and found defect-free.[59] In some cases,[76] cracking could not be detected radiographically, but was found after low ductility tensile failures were examined by metallographic inspection of longitudinal sections through the center of the weld. This propensity to delayed cracking is reminiscent of hydrogen induced cracking in other high strength steels, and investigation has indicated that at levels of hydrogen above about 3-5 ppm in the deposit, such cracking can be expected. It is mandatory to maintain stringent limits on filler analysis, joint cleanliness, and freedom of the joint or flux from moisture to preclude such cracking.

Hot Cracking. Hot cracking has taken several forms; centerline or solidification cracking in primary weld metal, reheat cracking in weld metal, and heat-affected zone cracking.

Centerline cracks (Fig. 43) characteristically occur down the coarse, columnar-grained trunk at the center of the deposit. They are typical of solidification cracking that occurs either in the liquid state or just below the solidus and are associated with brittle films. Figure 44 shows such films on the fracture face of a centerline crack.

Such cracking, and the embrittlement accompanying it, is composition dependent as indicated by the fact that its occurrence has varied with the flux employed. Strong evidence for this was obtained from an interesting experiment[74] in which weld metal from a centerline-cracked 1 in. submerged-arc weldment was machined out, swaged and ground to suitable size, and used to make a 1 in. TIG weld manually. This weld, made with pure inert-gas shielding, low heat input, and a large number of small passes (21 to fill the 1 in. joint), was fine grained and crack-free but its toughness of 6 ft-lb was identical to that of the submerged-arc weld. Thus, the embrittlement and tendency to centerline cracking seem related to such elements as manganese, silicon, carbon, and oxygen which come either from the flux itself, or because of the role played by the flux in slag metal reactions.

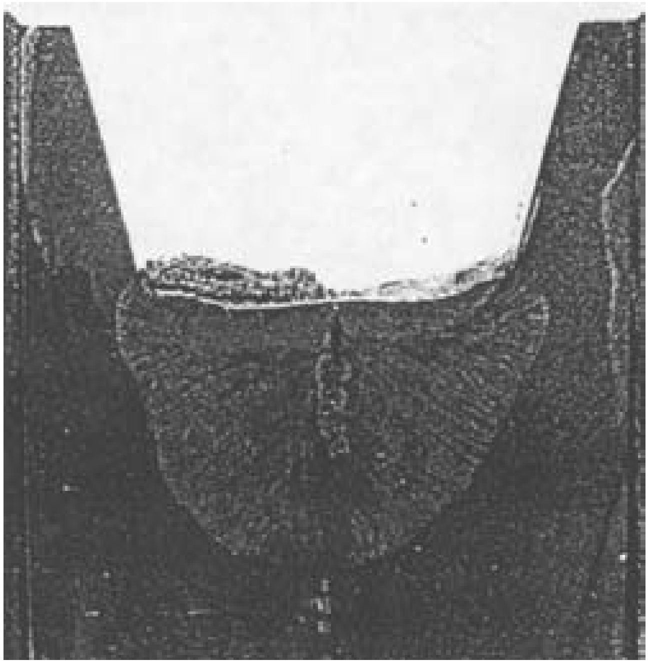


Fig. 43–Centerline cracking in the first pass of a submerged-arc weld in 18Ni (250) maraging steel. Etchant: Lepito's Reagent. X3 (Reduced 15%)

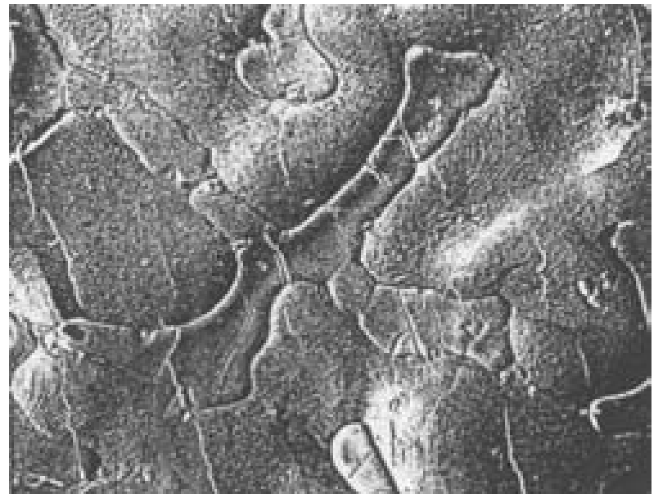


Fig. 44-Electron micrograph of fracture face of centerline crack in a submerged-arc weld in 18Ni (250) showing extent of brittle films. X6000 (Reduced 60%)

The general "dirtiness" of submerged-arc weld metal as shown by the number of inclusions present (Fig. 45) contributes to the ease of crack propagation.

The large number of inclusions in submerged-arc welds result from the relatively high levels of impurity elements and the high gas contents. A similarly large number of inclusions were seen in MIG welds made with a filler wire containing greater than normal amounts of titanium and nitrogen.[22] The fracture surfaces of submerged-arc welds are relatively flat and contain large, fragmented inclusions (Fig. 46). This is quite different from the more characteristic structure seen on the fracture surfaces of gas tungsten-arc and gas metal-arc welds. In submerged-arc welds the inclusions (probably TiCN) exert a dominant effect on fracture toughness. Even in the as-welded condition, the impact toughness of 18Ni (250) submerged-arc welds is low.

Since the flux is exerting such a strong influence one would predict that changes in weld wire composition would have little effect in improving the toughness or resistance to such cracking and investigators have confirmed this.

Reheat Cracking in Weld Metal. Virtually all attempts to produce multipass welds have failed be-

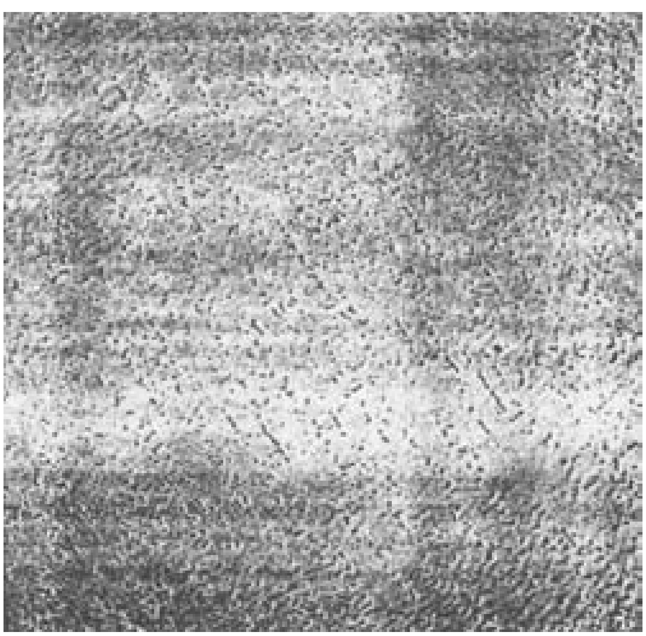


Fig. 45–Photomicrograph of submerged-arc deposit in 18Ni (250) showing extent of inclusions present. As-polished. X 100

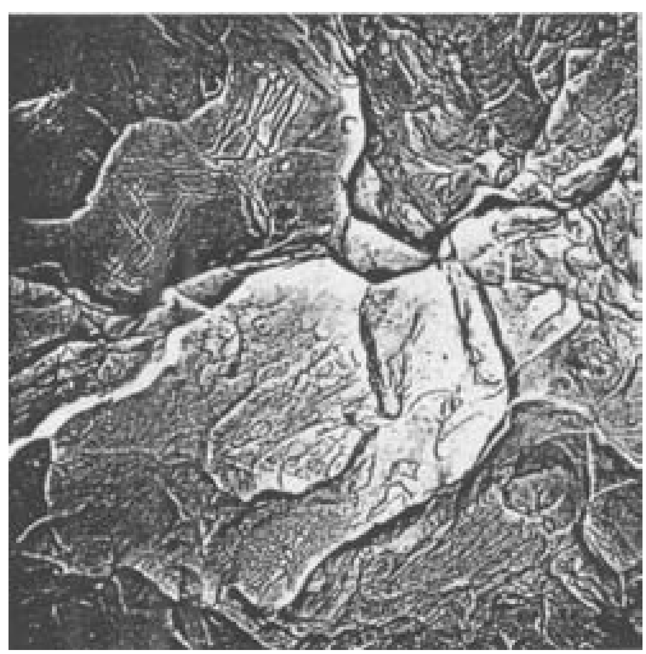


Fig. 46–The fracture face of submerged-arc welds typically contain a large number of inclusions. X 7500 (Reduced 50%)

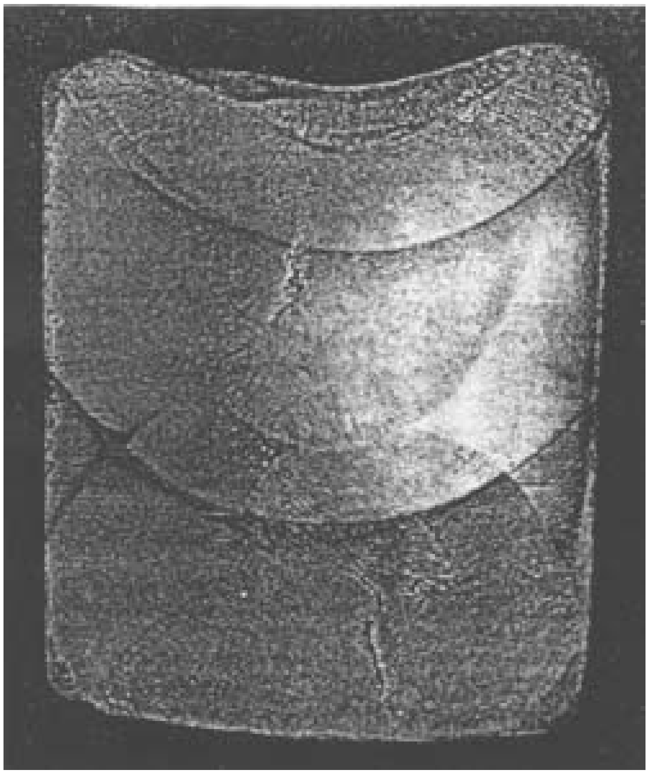


Fig. 47–Cracking in a rnultipass submerged-arc weld in 18Ni (250) showing cracking emanating from "eye-brow" regions. Etchant: modified Fry's. X3

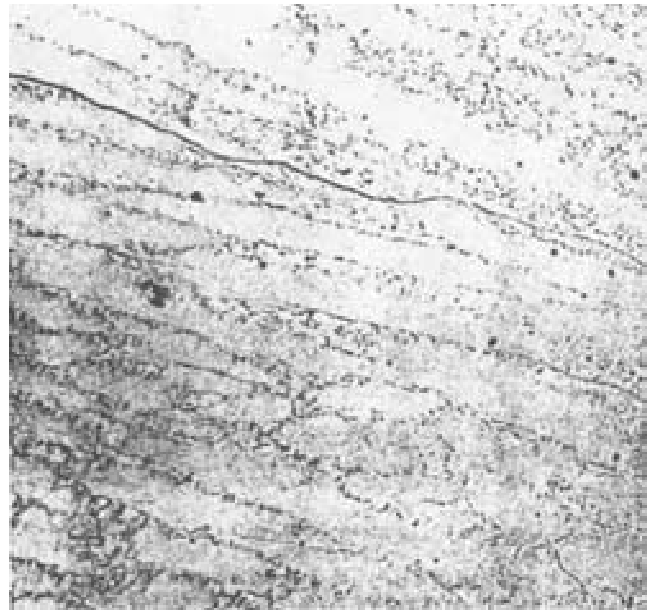


Fig. 48–Photomicrograph of portion of crack shown in Fig. 47 showing cracking to be intergranular. Etchant: chromic acid electrolytically. X3

cause of cracking, and many two-pass welds have also exhibited such defects. This cracking occurs in the underlying bead when another pass is deposited, and extends through the lower pass to a point beneath the root of the covering pass. Some of this cracking is similar to centerline restraint or shrinkage cracking, but much of it is not, as shown in Fig. 47. Though intergranular (Fig. 48) it appears to start within the region of the underlying pass that has been heated to only 1200 to 1300º F.

The fact that the cracking occurs in regions which are relativelv cold indicates that these cracks are different from the type of reheat cracks which characteristically emanate from the vicinity of the fusion line between passes. The exact causes of the cracking have not been determined, but contributing factors are the coarse unrefined structure, impurity segregation in the grain boundaries, austenite resulting from segregation, and titanium carbides, nitrides, and sulfides in the areas of austenite pools.[23,58,59] The damaging effects of these features are accentuated by the high heat inputs of the submerged-arc process. This explains why similar defects have very rarely been found in multipass weldments produced by other techniques.

Heat-Affected Zone Cracking. The soft and ductile solution-annealed zone adjacent to the fusion line of welds in the maraging steels aids in absorbing solidification stresses and minimizes the cracking which is often found in these areas in quenched and tempered steels. This is normally found to be the case, and little or no heat-affected zone cracking has been reported for inert-gas welds, but cracks have been found in material subjected to high energy inputs such as those used in the submerged-arc process. Several factors can be involved.

It is generally agreed that welds made with high energy inputs tend to embrittle the heat-affected zone as well as weld metal.[59,65,74] Such an embrittled zone was associated with the premature failure of a 260 in. SL-1 motor case.[77] While the exact nature of the embrittlement has not been established, it appears to be associated[23,58,74] with both grain boundary liquation (Fig. 49) and the solid state precipitation, during cooling, of titanium carbide or carbonitride particles (Fig. 50). It seems unlikely that this condition can be corrected unless lower heat inputs are employed, but such a limitation negates one of the advantages of the submerged-arc process.

Electroslag Welding

The electroslag process depends upon a molten slag to protect the weld metal, but, unlike the submerged-arc process, electroslag uses the molten, electrically-conductive slag rather than an arc to melt the filler metal. The process is particularly economical for welding heavy sections, and as a result, it has come to be associated primarily with the welding of plates ranging in thickness between about 1½ and about 12 in. This has inevitably restricted the use of the process, particularly in the USA, to the welding of carbon and low-alloy steels, but some interest has developed in welding higher alloy steels, stainless and nickelbase materials and much development work is in process. Some electroslag welding of 18% nickel maraging steel (250 ksi grade) was done in connection with fabrication of 3¾ in. thick rings for the 260 in.

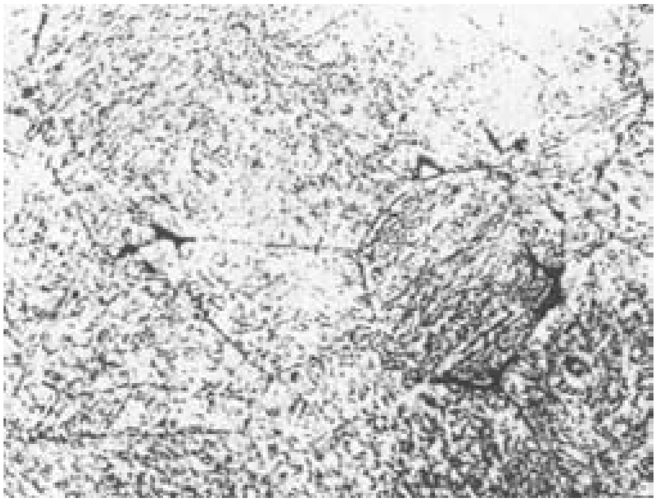


Fig. 49–Grain boundary liquation in 18Ni (250) maraging steel cycled to 2400° F at heat input representative of a submerged-arc weld. Note also the grain boundary particles. Etchant: modified Fry's Reagent. X500 (Reduced 20%)

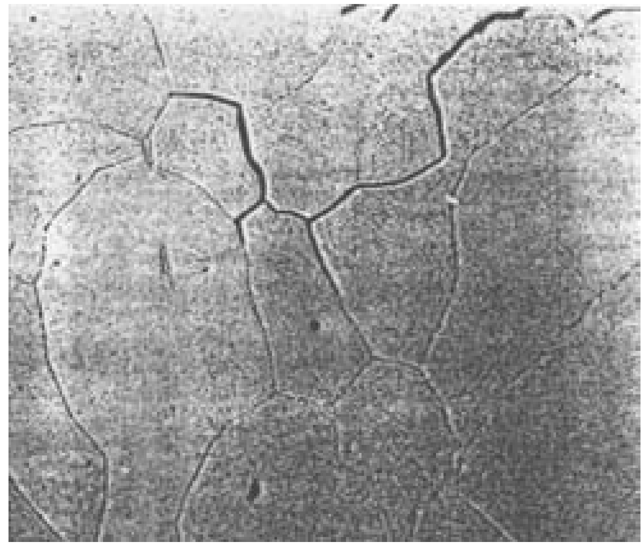


Fig. 50–Cracks along the grain boundaries in the heat-affected zone of a submerged-arc weld. Note the grain boundary particles. Etchant: modified Fry's Reagent. X750 (Reduced 15%)

SL-1 motor case.[41] More recently, there has been some experimental welding of the 12% Ni-5% Cr 3% Mo maraging steel.

Filler Wires and Fluxes. Fillers closely matching the composition of the parent metal are normally recommended for welding highly alloyed materials.[78,79] Clearly, such a "matching filler" approach is necessary for the maraging steels and welds made to date have employed such fillers. As with the other flux-shielded processes though, slag metal reactions result in the loss of the important reactive elements titanium and aluminum; therefore, fillers somewhat enriched in either or both of these elements are likely to be required. Though fillers have not been specifically developed for electroslag welding maraging steels, the comparison of filler wire and deposit compositions shown in Tables 18 and 19 for several electroslag welds in 18% nickel and 12% nickel maraging steels suggest the type of composition required.

Fluxes for electroslag welding, though similar in some respects to those used for submerged-arc welding, require a balance of characteristics that include good conductivity, uniform viscosity, and excellent stability necessitated by the nature of the electroslag process. These requirements are described in detail in refs. 78 and 79. Insufficient work has been done to define an optimum flux for the maraging steels, but experiments with several, indicated that a CaF_2-Al_2O_3-MgO flux operated well, provided sound welds and, in combination with matching composition wire, provided 12% nickel welds with reasonable property levels (Table 20).

Joint Design and Process Parameters. Joints in electroslag welding are square butt, usually with a 1 to 1½ in. gap between the plates to be joined. The smaller gaps are used for thinner plate (2-3 in. thick) and the larger gaps for thicker material. Rela-

Table 18-Filler Wire vs. Weld Metal Composition (%) Electroslag Welded 18% Nickel Maraging Steel

Element	Wire	Weld I	Weld 2	Weld 3	Weld 4
Titanium	1.20	0.43	0.72	0.63	0.75
Manganese	0.03	0.04	0.07	0.06	0.04
Silicon	0.01	0.38	0.08	0.07	0.05
Aluminum	0.15	0.12	0.12	0.07	0.08
Flux[a]		No. 1	No. 2	No. 2	No. 2

[a] Flux No. 1 commercial, proprietary composition. Flux No. 2 experimental, proprietary composition.

Table 19-Filler Wire vs. Weld Metal Composition Electroslag Welded 12% Nickel Maraging Steel

	Composition, %				
Element	*Filler wire*	*Weld No. 1*[a]	*Weld No. 2*[b]	*Weld No. 3*[c]	*Weld No. 4*[d]
Nickel	12.0	12.4	12.4	12.4	12.4
Chromium	5.0	4.9	4.9	4.9	4.9
Molybdenum	2.4	2.7	2.8	2.8	2.8
Aluminum	0.10	0.02	0.10	0.14	0.10
Titanium	0.43	0.10	0.33	0.27	0.24
Carbon	0.004	0.005	0.005	0.005	0.005
Phosphorus	0.002	0.004	0.002	0.002	0.002
Sulfur	0.004	0.003	0.005	0.006	0.008
Silicon	0.02	0.10	0.04	0-05	0.04
Manganese	0.01	0.05	0.05	0.05	0.05
Oxygen, ppm[e]	5/9	210	265	170	190
Hydrogen, ppm	3.5/4	ND[f]	ND	ND	ND
Nitrogen, ppm	21/23	54	60	73	65

[a] Commercial flux-composition proprietary.
[b] Flux–100% fluorspar (CaF_2).
[c] Flux–76% fluorspar, 24% alumina (Al_2O_3).
[d] Flux–71% fluorspar, 20% alumina, 9% magnesia (MgO).
[e] Parts per million.
[f] Not determined.

Table 20–The Strength and Toughness of Electroslag Welds

Alloy grade	*Specimen type*	*Specimen location*[a]	*Postweld treatment*	*0.2% Y.S., ksi*	*U.T.S., ksi*	*Elong., %*[b]	*R.A., %*	*Fracture location*	*CVN, ft-lb*
18Ni (250)	Across weld	Weld center	900° F, 3 hr	215	219	3	24	Dark band[c]	...
18Ni (250)	Across weld	Weld center	1650° F, 1 hr 900° F, 3 hr	238	243	6	28	Dark band	...
18Ni (250)	Parallel to weld	Weld center	900° F, 3 hr	235	250	6.0	11	Weld	...
12-5-3	Across weld	Weld center	900° F, 24 hr	156[d]	168	13	46	Weld metal	29
.12-5-3	Across weld	Fusion line	900° F, 24 hr	166	176	11	47	Part weld Part HAZ	58
12-5-3	Across weld	Dark band	900° F, 24 hr	170	179	13	63	Dark band	109
12-5-3	...	Base metal	900° F,24 hr	180	187	15	65	...	58

[a] Center of specimen gage length, centered at these points.
[b] In 2 in. for 18Ni weld and in 1 in. for 12Ni welds.
[c] Refers to dark etching heat-affected zone area heated to temperatures around 1200° F.
[d] Less than 0.10% aluminum and titanium in deposit.

tively short length welds or those in thinner gage material are assembled, using horseshoe-shaped clamps arranged so as not to interfere with the welding equipment of the sliding copper shoes that are used to retain the weld metal during solidification. More massive sections often provide adequate restraint to permit elimination of such clamps.

Welding currents are related to wire feed speed and thus deposition rate, but 550-650 amp dcrp has been commonly used in conjunction with 1/8 in. wire for a variety of materials including the maraging steels. Welding voltage with the same size wire typically ranges from 40-55 v but depends in specific instances on a variety of factors that are discussed in detail in the literature.

For joints between 1½ and 5 in. it is common practice to use a single 1/8 in. diameter wire with wire oscillation across the joint to insure proper fusion. For joints above 5 in. in thickness, multiple wires, or sometimes plate electrodes are used. In using oscillation, both speed and dwell time at the end of each stroke (to control fusion) must be balanced with respect to other variables. For welding 2 in. maraging steel, a 1 in. wire traverse in 1 sec with a 2 to 3 sec dwell time at each end of the traverse proved satisfactory.[80]

In electroslag welding a slag pool depth of 1½ to 2 in. is said to be optimum and has been used in welding the maraging steels.

Mechanical Properties. With a proper deposit composition, weld strength tends to be uniformly high with fracture often occuring in the dark etching region of the heat-affected zone (Table 20). If the weld wire is not sufficiently fortified to make up for the loss of reactive hardening elements during welding, low strength weld metal failures can be expected.

The ductility of 18% Ni weld metal, particularly the reduction of area, tends to be low, perhaps 1/3 to ½ of the values for base plate but comparable to those obtained in welds made by other flux shielded processes. Available data for welds in the 12% nickel alloy suggest that their ductility is closer to that of the parent alloy.

Fracture toughness (K_{IC}) or CVN values have not been published for 18% Ni weldments, but critical flaw sizes averaging 0.165 in. were found for electroslag welds.[41] These are comparable to values obtained in conventional submerged-arc welds but are only 1/3 to ½ those of parent metal or welds made by the gas tungsten-arc process.

The CVN values for electroslag welds in the 12Ni steel indicate similar behavior, and the fusion line area of these welds maintained relatively high toughness. It is noteworthy that the toughness of the dark etching band in the 12% nickel welds (Fig. 51) is substantially higher than unwelded base plate. This behavior has been observed before[18] and is thought to occur because of the presence of finely distributed particles of soft stable austenite in this area.

Defects and Their Control. If welding conditions are not carefully set and maintained, defects such as cracking, porosity, and lack of fusion do occur in electroslag welds. These are discussed in considerable detail by Paton.[79] It is appropriate to mention however that, to the extent the process has been employed in this country, welding defects have been relatively infrequent. The only defects seen in the welds made in maraging steel have been in the run-on, run-off areas which are removed following welding.

VII. Electron Beam Welding

Electron beam welding offers several advantages over arc welding processes, notably a high depth to width ratio in the fusion zone, a very small heat-affected zone, cleanliness, and minimum distortion. These features make the process attractive and as a result it is being considered for an increasing number of applications involving a variety of alloys.

Joint Design and Process Parameters

Electron beam welds have been made in several thicknesses of maraging steels, from thin sheet to moderately thick plate. In all cases, the edges to be welded were machined to close tolerances to ensure the proper fit-up that is an essential part of making good electron beam welds. The pieces were also

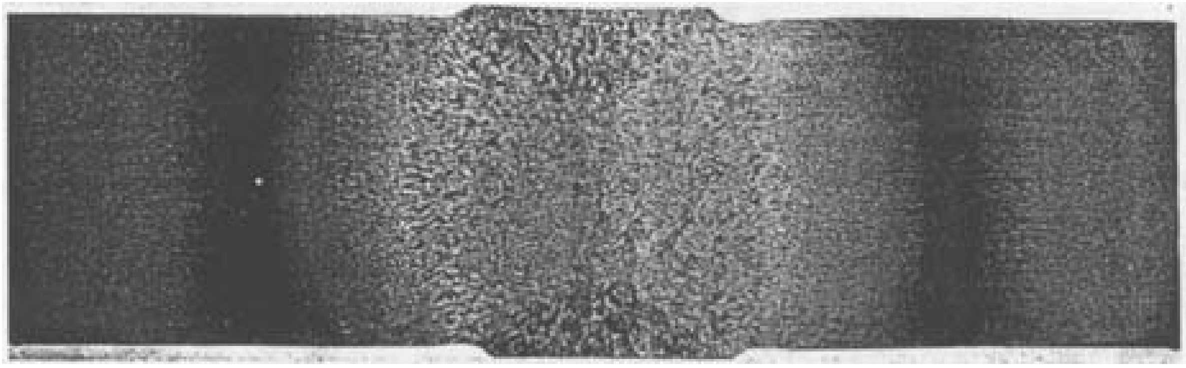


Fig. 51-Cross section *of* an electroslag weld in 12-5-3 maraging steel showing the general structure and extent *of* the dark band or "eyebrow."Etchant: Lepito's Reagent. X 1 (Reduced 10%)

cleaned with solvents.

Welds have been made with both high and low voltage equipment, and with a variety of welding conditions as Table 21 shows. This table also summarizes the mechanical properties of the welds which are discussed in the following section.

Mechanical Properties of Electron Beam Welds

Electron beam welds that were aged after welding had strengths as high as the strengths of the plates (100% joint efficiency). The ductilities, as measured by reduction of area, were about half the base plate values, and the weld toughnesses were also below those of the plates. In fact, the toughnesses of the electron beam welds were below the values normally obtained in MIG welds of the same steels.[81,82] In one study the weld toughness was improved by solution annealing after welding and before aging.[83] But in other instances this heat treatment had little effect on tensile ductility[26,84] and so its effectiveness must remain in doubt.

As would be expected, the strengths of welds that were not aged after welding were lower than those of the solution annealed and aged base plates. The joint efficiencies varied with the welding conditions and plate thicknesses. One as-welded value of 242 ksi for the strength of a weldment in the 18Ni (250) steel[84] is remarkably high in view of the fact that the true strength of the weld zone is approximately 130 ksi. This seems to be an example of a thin soft zone being supported effectively by surrounding stronger material. Microhardness surveys showed the fusion zone to

Table 21-The Mechanical Properties of Electron Beam Welds and the Welding Conditions Used to Make the Welds[a]

	Welding conditions				*Mechanical properties*					
Grade & plate thickness	*No. of passes*	*Voltage, kv*	*Current, mamp*	*Travel speed, ipm*	*Heat treatment*[b]	*0.2% Y.S., ksi*	*U.T.S., ksi*	*Elong., %*[c]	*R.A., %*	*Weld toughness K_{IC} or CVN*
18Ni (250) 0.1 in.	*1*	*Unwelded*			*SA*	*255.6*	*265.8*	*5.7*	*28.3*	
		30	*65*	*40*	*SAWA*	*270.8*	*274.4*	*4.1*	*12.7*	
		30	*65*	*40*	*SAW*	*165.8*	*165.8*	*2.5*	*21.2*	
		30	*65*	*40*	*SWSA*	*258.1*	*263.5*	*3.2*	*12.7*	
18Ni (250) 0.295 in.	*1*	*Unwelded*			*SA*	*264.0*	*267.0*	*15*	...	
		150	*20*	*60*	*SAWA*	*262.0*	*265.0*	*4*	...	
		150	*20*	*60*	*SAW*	*242.5*	*242.5*	*4*	...	
		150	*20*	*60*	*SWSA*	*272.0*	*275.0*	*5*	...	
18Ni (250) 0.5 in.	*1*	*Unwelded*			*SA*	*248.0*	*260.0*	*22*	*51*	
		150	*17*	*17*	*SAWA*	*250.0*	*261.0*	*14*	*25*	
		150	*17*	*17*	*SAW*	*181.0*	*189.0*	*8*	*30*	
18Ni (200) 1.0 in.	*2*	*Unwelded*			*SA*	*207.0*	*214.0*	*23*	*56*	
		150	*13*	*10*	*SAWA*	*212.0*	*217.0*	*7*	*14*	
		150	*13*	*10*	*SAW*	*160.0*	*168.0*	*10*	*32*	
18Ni (250)	*1*	*Unwelded*			*SA*	*252.3*	*259.9*	*12*	*50.4*	*87.5 ksi (in.)$^{1/2}$*
1.0 in.		*50*	*320*	*40*	*SAWA*	*256.1*	*260.2*	*4*	*27.8*	*68.0 ksi (in.)$^{1/2}$*
		50	*320*	*40*	*SWSA*	*255.6*	*257.4*	*6.5*	*41.3*	*72.6, 85.6 ksi (in.)$^{1/2}$*
18Ni (200) 1.0 in.	*1*	*50*	*400*	*40*	*SAWA*	*196.0*	*198.0*	*4*	*13*	*20 ft-lb*
		50	*400*	*40*	*SAW*	*147.0*	*151.0*	*7*	*31*	*14 ft-lb (defects)*
12-5-3 1.0 in.	*1*	*50*	*400*	*40*	*SWA*	*181.0*	*187.0*	*10*	*35*	*20 ft-lb*
		50	*400*	*40*	*SW*	*135.0*	*147.0*	*13*	*67*	*62 ft-lb*
		50	*400*	*40*	*SAWA*	*181.0*	*186.0*	*9*	*33*	*15 ft-lb*
		50	*400*	*40*	*SAW*	*130.0*	*147.0*	*13*	*61*	...

[a] All the welded samples failed in the weld.

[b] S = solution annealed, A = aged, W = welded.

[c] The tensile elongations must be treated with caution since the weld metal sometimes constitutes only a small portion of the gage length.

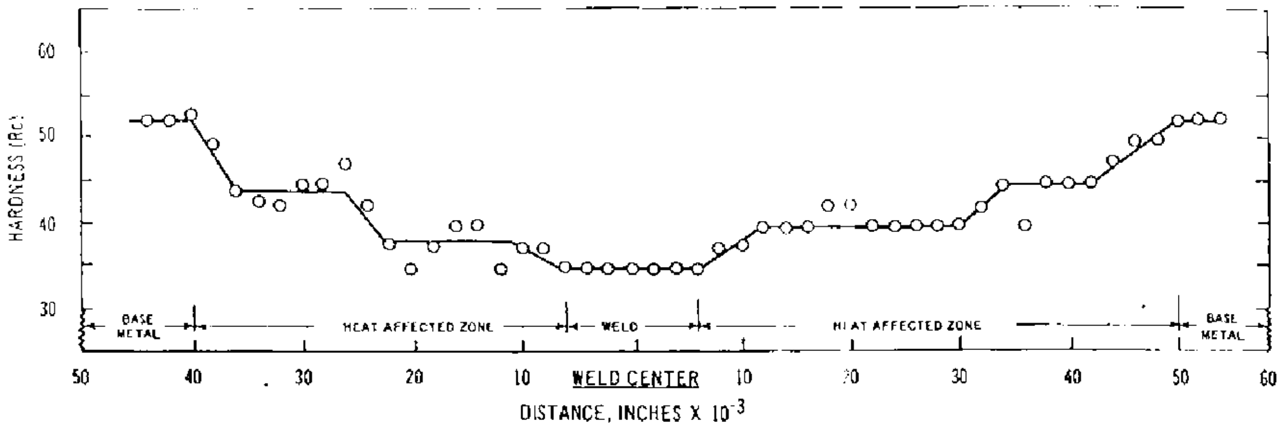


Fig. 52–Hardness profile of 18% Ni maraging steel; solution annealed. aged and electron beam welded

be 0.01 in. wide (Fig. 52). Narrow weld beads and small heat-affected zones are features of electron beam welds. Adams[17] noted that in electron beam welds in maraging steels, the dark etching region in the heat-affected zone was almost eliminated.

The last set of results in Table 21 show that the starting condition of the base plate, whether solution annealed or solution annealed and aged, had no effect on the weldment properties.

Defects in Electron Beam Welds

Cold shuts, porosity, and lack of fusion have been observed in electron beam welds in maraging steels. [26,82,83] Examples are given in Figs. 53 and 54.[26] Similar defects have been seen in titanium and nickel-base alloys and in other high-strength steels.[83,85] Electron beam users have confirmed that weld defects are a problem in many alloys, particularly when welding thick sections.[83]

As the plate thickness increases the more difficult it becomes to achieve the very precise joint fit-up and accurate alignment of joint with gun that are necessary if the welds are to be properly fused. Residual magnetic fields in the plates compound the difficulties by deflecting the electron beam.

When welding 1½ in. thick maraging steel plate with one pass from each side, the. beams were deflected sufficiently to cause weld misalignment with the result that, in the center of the joint, the two passes did not overlap. The unfused region was seen when sections were examined metallographically although it had passed undetected in a radiographic examination. To avoid these buried defects it was recommended that the welds be made in one pass.[83]

Apart from the process difficulties, however, there is evidence that metallurgical factors contribute to the occurrence of weld defects. For example, since the welds are usually made without filler wire the quality of the plate becomes very important. Fragetta and Krysiak[82] attributed the variety of defects they encountered in electron beam welds in an 18Ni (200) maraging steel to the poor quality of the air-melted

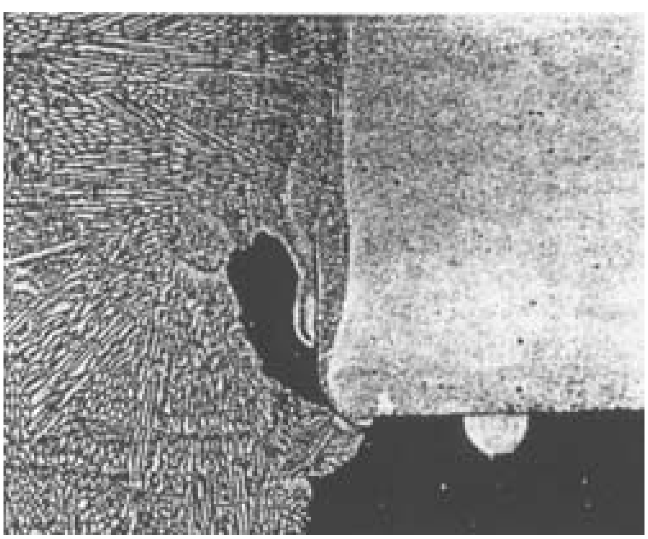


Fig. 53–Weld root defects in a full penetration melt run in 0.185 in. thick 18% Ni/Co/Mo steel sheet with ground surface. Etched in 15% nital. X 150

Fig. 54–Secondary cracks in weld metal close to fusion boundary, etched in 5% nital. X 150

plate. In other work,[26] incomplete wetting of oxides and impurity segregation were said to be responsible or the root and fusion line defects. The segregation and unfavorable orientation of the weld deposit have also been blamed for the poor toughness and low ductilies of electron beam welds in maraging steels.[82,86]

It seems likely that the weld defects are caused by certain metallurgical features of maraging steels as well as by the characteristics of the electron beam process. The relative contributions however are difficult to assess and it is not surprising that there have been calls for more research to define the effects of welding parameters and material composition on the occurrence of weld defects.

Application of Electron Beam Welding

An analysis of the published information on the electron beam welding of maraging steels leads to the conclusion that it is difficult to make sound welds consistently, particularly in thick plate. However, the process is being used to weld maraging steels[87-89] and so it may be that practice is ahead of the pubished information. The type of defects discussed here apparently were encountered but have been eliminated by changing the welding conditions. An example is the use of slower travel speeds and wider beads to avoid the side-wall cold shuts.[90]

When sound welds are made their strengths after aging can be expected to match that of the plate but he ductilities will be considerably less. This has led some to conclude that electron beam welding has no particular advantage over more conventional methods for joining maraging steels in thick plate.[82,85]

VIII. Resistance Welding of Maraging Steels

A relatively small amount of work has been done on the resistance welding of maraging steels, and few results are available. The information is concerned mainly with flash butt welding, but there are some results on spot welds and high frequency seam welds.

Flash Butt Welding

The quality of flash butt welds in maraging steels is illustrated by the results of tension tests on transverse samples from the welds (Table 22). Samples from good welds fail in the base plate and consequently exhibit the full properties of the unwelded plate. While this behavior is not uncommon, there have also been weld failures with very low ductilities, sometimes before reaching the 0.2% offset. Such weld failures are characterized by large flat spots visible on the fracture surface and examination of a section through the weld gives some insight into the cause of the brittle failure. The examination reveals that bands of segregation and stringers in the base plate have been deflected through 90 deg by the upsetting action of the welding process (Fig. 55). When samples are tested, the planes of weakness are approximately at right angles to the applied stress and fracture can progress preferentially down the weak planes with little energy absorption. This produces the fracture surface flat spots. The relationship between the flat spots and the planes of weakness is shown well in the notched sample in Fig. 56. There, the contour of the surface flat spots can be seen to follow exactly the path of a deflected band.

Table 22-Tensile Properties of Flash Butt Welds in 1 in. Diameter 18Ni (250) Maraging Steel[a]

Specimen No.	*0.2% Y.S., hsi*	*U.T.S., ksi*	*% Elong. (in 3 in.)*	*R.A., %*	*Location of failure*
1	246.9	254.3	10.0	56.0	Base plate
2	252.5	255.9	1.3	6.0	Weld
3	[b]	213.0	...	...	Weld

a Welds aged at 900° F for 3 hours.
b Fractured before 0.2% offset.

Table 23-Tensile-Shear Strengths of Spot Welds in 18Ni (300) Maraging Steel

Specimen condition	*Tensile-shear load, lb*	*Hardness, Rc Weld*	*Hardness, Rc HAZ near fusion line*
As-welded	4950	32	32
Welded + aged 900° F/1 hr	5050	47	50

Failures have been seen from time to time in flash welds of many highly alloyed. materials from aluminum-base to nickel-base and were reported several years ago in flash butt welds of a modified 4340 steel.[91] There also, brittle premature failures were traced to a banded structure that had been turned 90 deg by the welding process. The implication is that flash butt welds made in plate that was free from these planes of weakness should have good ductility, and there is some evidence that this is so. Notched samples from welds made in an 18Ni (200) maraging steel that appeared free of bands (Fig. 57) broke in a ductile manner and there were no flat spots on the fracture surface (Fig. 58).

Resistance Spot Welding

Spot welds have been made in 0.064 in. thick by 1½ in wide sheet of 18Ni (300) maraging steel in the aged condition, using the following welding schedule:

4000 lb. forge force
50% weld phase shift
20001b. weld pressure
16 cycles heat time
9.5 cycles cool time
1 impulse weld time
50 cycles forge after weld

The nugget thickness, was 0.079 in. representing approximately 60% penetration, and the diameter of the fused area was approximately 0.230 in.

The tensile-shear loads and the hardnesses of the joints tested as-welded and after aging are shown in Table 23. All the samples failed by shear through the

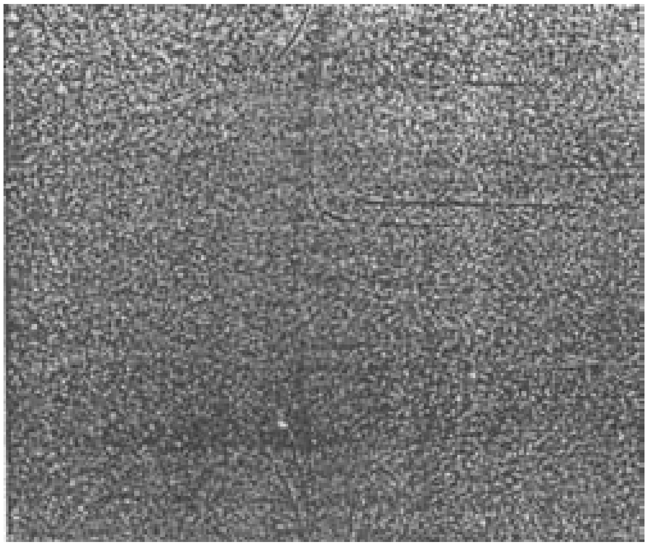


Fig. 55–Flash weld in 18Ni (250) maraging steel showing upsetting of dark-etched bands. X3

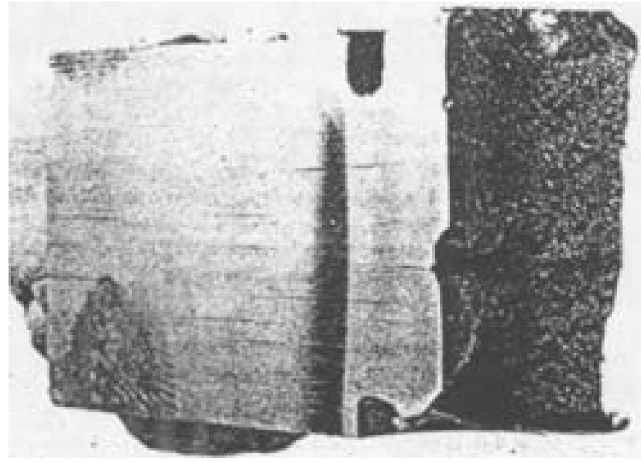


Fig. 56–Fracture surface of flash butt weld. Surface flat spot follows line of dark-etching band. X2

weld metal. Although a post-weld aging treatment (900° F/1 hr) produced the expected increase in the hardness of the weld metal, the aged samples failed at almost the same load as the as-welded ones. When the failure loads were divided by the area of the interface, all the samples had strengths of 80 to 90 ksi. The joint failure loads appear to fall within the range expected for material of this strength and thickness, and the manufacturer considered the joints to be of aircraft quality. On the other hand, since the strengths of the joints after aging are the same as in the as-welded condition, it is obvious that the high strength of the steel is not being utilized.

On the basis of these few results therefore, spot welding can be said to have shown promise, but more work would be needed before the process could be recommended for maraging steels.

High Frequency Resistance Welding

High frequency resistance welding of a variety of high strength steels, among them 18% nickel maraging steel, has been studied. Butt seam joints in 0.188 in. material had efficiencies above 60% in the as-welded condition and 90-100% after aging. Helically welded cylinders 24 in. in diameter and containing about 60 ft of weld seam were produced .[92]

IX. Other Joining Techniques

Dissimilar Metal Joints

Little has been published concerning the applicability or use of maraging steels in dissimilar metal joints, but the work that has been done does not suggest any unique problems. Since maraging steel is most likely to be joined to other steels, and probably by fusion welding, data given here will be restricted to such joints.

Maraging Steel Characteristics as They Affect the Dissimilar Joint. Each joint between different materials is unique and requires critical review of both design and metallurgical considerations if it is to operate successfully under the stresses and environments expected. It is clearly beyond the scope of this report to cover the many factors involved. They have been discussed in detail in the literature.[93-95] Some of the important considerations are discussed below

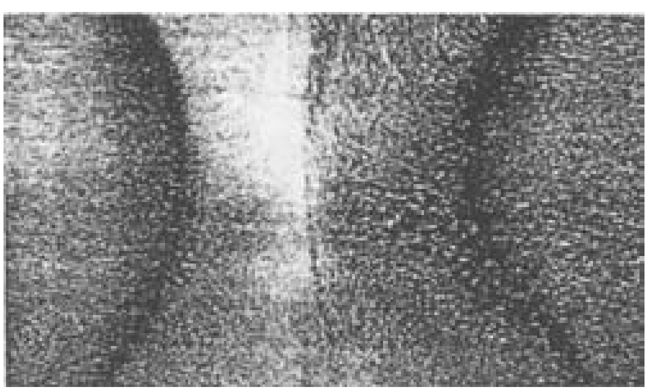


Fig. 57–flash weld in 18Ni (200) maraging steel that is free from banding

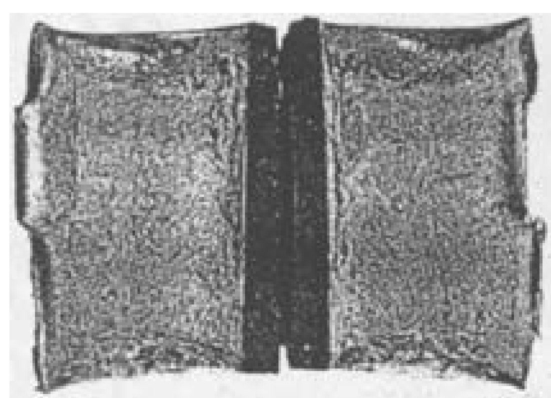


Fig. 58–Fracture surface of 18Ni (200) flash weld. Note absence of flat spots. X3 (Reduced 50%)

Table 24-Comparative Thermal Properties

Material	Average coefficient of linear thermal expansion betuween 20-500° C (68-932° F) (in./in. °C)	Thermal conductivity at 100° C (212° F) call (sec) (cm²) (°C/cm)
Carbon steel[a]	13.1-14.5	0.107-0.138
Low alloy steel[a]	13.1-14.3	0.081-0.111
Chromium stainless steel[a]	10.8-12.1	0.059-0.062
Austenitic stainless steel[a]	17.2-18.5	0.030-0.039
18% Ni (250) managing steel[b]	10.1	0.050

a From Metals Handbook, 1948 Edition.
b Data bulletin, 18% Ni Managing Steels, The International Nickel Company, Inc., 1964.

with reference to maraging steels.

Thermal Properties. The differences in conductivity between maraging steel and the other materials shown in Table 24 should not create any difficulty, but welding conditions should be adjusted to provide higher heat input, or possibly preheat, to the metal with the greater conductivity.

The differences in thermal coefficients of expansion can set up stresses in restrained joints, both during welding, and in service entailing cycling over a wide temperature range. Difficulties could arise as differences in expansion between joint members increase; e.g., between maraging steel and austenitic stainless. Cracking in the heat-affected zone of a weld between 347 stainless steel and 18Ni (250) confirms this possibility.[96]

Composition Effects. Dilution by carbon, sulful, phosphorus, or silicon will reduce ductility and toughness, while dilution by carbon or manganese, or large changes in composition balance will reduce the degree of hardening possible.

Response to Heat Treatment. The postweld heat treatment of joints between maraging steel and other steels must depend upon the dissimilar alloy member involved, the joint strength required, and the conditions under which the joint is to be used. For example, in joints between maraging steel and high-chromium ferritic stainless, aging the joint at 900° F could produce the well known 885° F embrittlement of the latter material. Similarly, welds between maraging steel and carbon-hardened materials should be heat treated in such a way as to balance aging of the maraging steel with tempering of the carbon-hardened steel for optimum strength.

Corrosion Resistance. The corrosion resistance of 18Ni maraging steel in industrial atmospheres, marine atmospheres, and in sea water is about twice that of the low-alloy steels HY-80 and 4340.[97] Depending upon service conditions, and the other member of a dissimilar joint, galvanic corrosion may be a serious problem. To minimize the difficulty, the weld deposit composition should be selected to provide cathodic protection to the joint member that is most susceptible to galvanic attack.

Preparation and Properties of *Dissimilar Joints.* In a study to produce a leaf spring that could withstand high impact loading, 18Ni (250) was fillet welded to ASTM A-201–Grade B and A-242 using a variety of fillers and .processes.[98] Satisfactory joints were produced with all combinations of processes and wires (Table 25). The preparation of satisfactory butt joints between 1/8 in. 18Ni (200) and carbon-manganese steel using several fillers and welding techniques has also been reported .[94]

In work done by The International Nickel Company, Inc.,[51] ½ in. butt joints were produced between 18Ni (250) and mild steel, HY-80, SAE 4340, and 304 stainless steel. The results showed, Table 26, that sound joints could be produced without difficulty and, that as one would expect, the strength of a particular joint was governed by the weakest material of the combination. An overlay of maraging steel weld metal

Table 25-Fillet Welds Between 18% Nickel Maraging Steel and Carbon Steel

Filler material							*Weldment properties*		
Designation	*Diam, in.*	*Process*[a]	*Current dcrp, amp*	*Voltage*	*Welding speed, ipm*	*Maraging to ASTM grade*	*U.T.S., ksi*[b]	*Shear strength, ksi*[b]	*Tensile impact, ft-lb*[c]
INCONEL welding electrode 182	5/32	SMA	125	25	5	A-242	76	49	99-123
						A-201	77.5	48.4	119-139
E308-16ELC	¼	SMA	260	22	8	A-242	83.2	48.8	114-142
						A-201	74.1	51.5	129-163
308ELC	0.045	GMA Short circuit	170	21	14	A-242	73.7	48.4	116-160
						A-201	87.4	49.2	127-184
INCONEL filler metal 82	0.062	GMA Spray	240	26	20	A-242	78.8	58.8	108-129
						A-201	83.2	56.0	132-148
Maraging steel	0.062	GMA Spray	240	25	20	A-242	Failed in A-242	Failed in HAZ A-242	109-141
						A-201	Failed in A-201	Failed in HAZ A-201	124-159

a SMA = shielded metal-arc, GMA = gas metal-arc.
b Average for 3 tests, ¼ in. double fillet.
c Range of 3 tests.

Table 26-Properties of ½ in. Thick Welded Joints Between 18% Ni 250 Maraging Steel and Various Dissimilar Metals

			Transverse weld properties											
			As-welded properties						*Aged (900° F/3 hr) properties*					
Metal being joined	*Filler material*	*Welding process*	*0.2% Y.S., ksi*	*U.T.S., ksi*	*El. %*	*R.A., %*	*Break[b]*	*CVN, ft-lb*	*Y.S., ksi*	*U.T.S., ksi*	*El., %*	*R.A., %*	*Break*	*CVN,[c] ft-lb*
Mild steel	Inco-Weld A	SMA	57	69	16	67	P	80	47	68	16	66	P	98
HY-80 steel	Inco-Weld A	SMA	55	88	14	43	W	78	58	89	10	29	W	72
4340 steel	Inco-Weld A	SMA	56	94	13	45	W	80	61	100	12	34	W	69
304 stainless	Inco-Weld A	SMA	51	89	26	34	W	95	54	91	36	79	P	97
Mild steel	18%Ni maraging[d]	GMA	63	70	6	65	P	25	50	67	5	65	P	16
HY-80 steel	18%Ni maraging	GMA	109	116	8	59	P	22	108	116	7	58	P	10
4340 steel	18 % Ni maraging	GMA	147	161	4	13	W	16	170	180	4	13	P	8
304 stainless	18%Ni maraging	GMA	62	90	23	76	P	28	61	90	32	75	P	14

Weld Conditions	*SMA*	*GMA*
Amperes	125 A	280/290 A
Volts	24 V	32 V
Travel	6 ipm	10 ipm
Wire feed	Manual	200 ipm
Heat input	30 Kj/in.	50/55 Kj/in.
Filler	5/32 in. rod	0.062 in. Wire
Preheat	None	None

[a] 0.252 in. diameter round tensile bar, 1 in. gage length.
[b] Break = location of tensile fracture, W = weld, P = dissimilar metal being joined.
[c] Notched through weld, notch axis normal to plane of plate.
[d] Filler contained 17.9Ni, 8.1Co, 4.9Mo, 0.5Ti, 0.13A1.

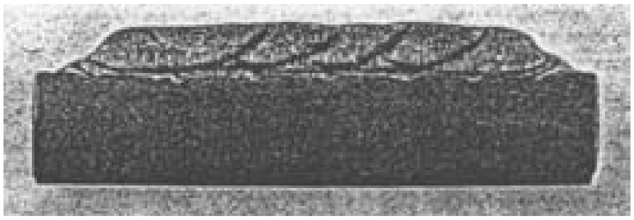


Fig. 59–Three-layer gas metal-arc 18% Ni maraging steel overlay on 1 in. mild steel. Etchant: Lepito's Reagent. X 1 (Reduced 40%)

on mild steel was also shown to be feasible (Fig. 59).

Both the 18Ni (250) and 18Ni (300) grades have been used as replacements for H-13 in aluminum die casting dies, and because of their excellent weldability, have also been used to repair weld the H-13 dies.[99,100] The use of these alloys to surface forging dies[101] and for general overlaying[102] has also been reported.

Brazing

Basic Considerations. There are no brazing problems unique to these steels, but several of their characteristics should be kept in mind.

1. Since they contain aluminum, titanium, and sometimes chromium, good wetting requires control of atmospheres and brazing procedures.
2. Temperatures in the austenite reversion range should be avoided unless the component is to be re-solution treated prior to final aging.
3. Temperatures over about 1800º F result in grain coarsening which can reduce the toughness and ductility of the steel.

Filler Alloys. Berry[103] investigated a number of palladium bearing alloys containing copper, nickel, silver, and manganese, and in one case, lithium (Table 27). All the vacuum brazed joints were satisfactory, but neither the silver-palladium-manganese, nor copper-silver-palladium-lithium alloys produced satisfactory torch brazes. In more recent work[104] on torch and furnace brazing a number of less expensive silver-copper and silver-copper-zinc alloys were examined (Table 27). With the proper procedures all provided satisfactory joints.

It is evident that there are a number of alloys which can yield satisfactory joints, but the desirability of restricting time at temperatures above about 1600º F indicates that those fillers with brazing temperatures in the range of 1475-1600º F should be most satisfactory. These fillers are available as both wire and foil, and which ultimately is used will be a matter of availability and joint design. To assure adequate wetting and flow, preplated shims should be used where possible.

Brazing Conditions and Techniques. *As* previously mentioned, titanium, aluminum, and chromium form stable tenacious oxides that inhibit wetting by brazing alloys. In this respect the maraging steels are similar to high temperature alloys such as Rene 41,* INCONEL alloy X-750, † and so on, and procedures established for brazing these alloys should be generally applicable.[105] These require excellent vacuums, very dry reducing atmospheres, or other procedures used to minimize the presence of oxides.

For furnace brazing, high vacuum atmospheres can clearly be used with satisfactory results as indicated by Berry's work.[103] Hydrogen or argon atmospheres can also be used successfully, but since they will not reduce stable oxides at temperatures between 1400 and 1600º F, the use of either flux, or plated surfaces is mandatory. Table 28 shows that with a normally dry welding-grade argon, flux must be used to achieve good flow and braze coverage. These data also show that it is possible to eliminate flux entirely, providing the surfaces are first preplated. While the data shown are for specimens brazed in dry hydrogen, a dry argon atmosphere should be equally useful.

For torch brazing, the use of a flux is clearly mandatory, whether or not a preplate is used, although the latter technique does improve braze coverage and strength.

Joint Properties and the Effects of Clearance and Overlap. The degree of overlap in single-lap shear specimens has a marked effect on shear strength as shown in Figs. 60 and 61 with strength decreasing rapidly as the overlap is increased. This is characteristic of brazements, because as the overlap increases, the greatest part of the load is carried by the

*Registered trademark of Allvac, a Teledyne Company.

†Registered trademark of The International Nickel Company, Inc.

Table 27-Brazing Alloys Investigated

	Nominal composition, %					*Approximate*	*Approximate*	
Alloy	*Cu*	*Ni*	*Ag*	*Pd*	*Other*	*liquidus, º F*	*brazing temp, º F*	*Processes examined*
1	55	15	...	20	10Mn	2021	a	Vacuum
2	...	48	...	21	31-Mn	2048	a	Vacuum and torch
3	50	15	...	35	...	2140	a	Vacuum
4	27	68	...	5	...	1490	1525	Vacuum, furnace, torch
5	82	...	...	18	...	1994	a	Vacuum and torch
6	...	...	75	20	5Mn	2048	a	Torch
7	27.8	...	52	20	0.2Li	1634	a	Torch
8	40	1.0	54	...	...	1575	1600	Furnace
9	28	...	72	...	...	1435	1475	Furnace and torch
10	27.8	...	72	...	0.2Li	1410	1500	Furnace
11	53.0	...	9	...	38Zn	1600	1600	Furnace and torch

[a] Not reported.

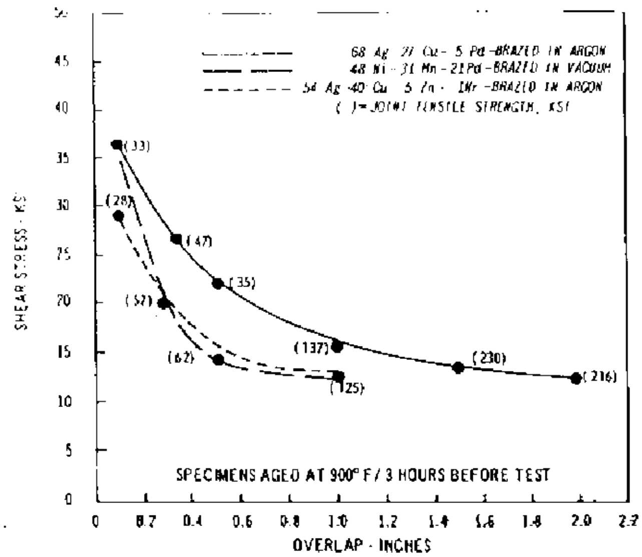


Fig. 60–Shear stress vs. overlap–furnace brazing

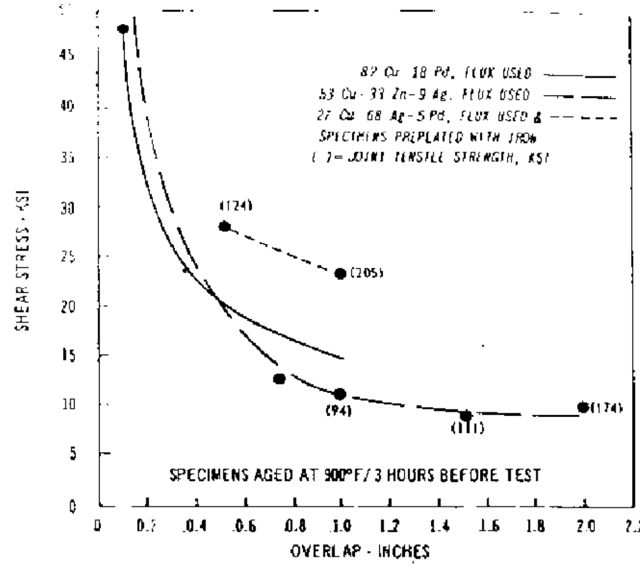


Fig. 61–Shear stress vs. overlap–torch brazing

ends of the joint while the central portion carries little load. In spite of the decrease in specific shear stress the tensile strength of the joint increases as the overlap increases. Joint clearance, like overlap, affects joint strength. Figure 62 shows that the narrower the gap, the higher the strength. "Contact clearance," that is about 0-0.0015 in., provides the best strength, and a gap of about 0.006 in. reduces the strength to about 70% of its initial level.

Inertia Welding

Table 29 gives the tensile properties of some inertia welds made between 1 in. diameter bars of 18Ni (250) maraging steel.[106] Though the samples broke in the welded region, they did not fail along the bond zone. The strengths are comparable to those of the unwelded material, and ductilities are good.

Fracture surface flat spots, seen in flash butt welds, do not occur in inertia welds because of the mixing that takes place in the bond zone.

Laser Welding

It is reported that 18% Ni maraging steel was satisfactorily laser welded and that welds displayed tensile strengths equivalent to the parent alloy.[107]

Table 28-The Effects of Flux and/or Preplating on Braze Coverage

Alloy type	*Atmosphere*	*Flux*[a]	*Preplating*[b]	*% Braze coverage by X-ray*
68Ag-27Cu-5Pd	Dry welding Grade argon	No	No	70
68Ag-27Cu-5Pd	Dry welding Grade argon	Yes	No	98
72Ag-28Cu	Dry welding Grade argon	No	No	5
72Ag-28Cu	Dry welding Grade argon	Yes	No	80
54Ag-40Cu-5Zn-1Ni	Dry welding Grade argon	No	No	30
54Ag-40Cu-5Zn-1Ni	Dry welding Grade argon	Yes	No	98
72Ag-27.8Cu-0.2Li	Dry welding Grade argon	No	No	0
68Ag-27Cu-5Pd	Dry welding Grade argon	Yes	No	90-100
68Ag-27Cu-5Pd	Dry welding Grade argon	No	Yes	50- 60
68Ag-27Cu-5Pd	Dry(-60° F)H_2	No	Yes	97- 99
68Ag-27Cu-5Pd	Dry(-90° F)H_2	No	No	0- 10
68Ag-27Cu-5Pd	Dry(-90° F)H_2	No	Yes	85-100

[a] Commercially-available "high temperature" flux.
[b] 0.0003-0.0005 in. of iron.

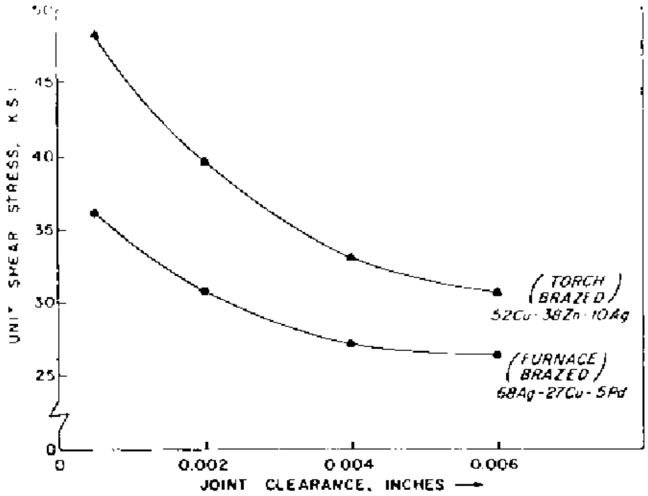


Fig. 62–Average unit shear stress as function of joint clearance at an overlap of 0.1 in.

Table 29-Tensile Properties of Inertia Welds in 1 in. Diameter 18Ni (250) Maraging Steel[a]

Specimen	*0.2% Y.S., ksi*	*U.T.S., ksi*	*% Elong. (in 2 in.)*	*R.A., %*
Unwelded bar	255.0	262.0	12	58
Inertia wled[b]	250.5	259.1	7	35
Inertia weld[b]	250.5	258.0	7.5	36
Inertia weld[b]	252.9	258.0	7.5	40
Inertia weld[c]	260.4	263.5	7.3	38

[a] Welds aged at 900° F for 3 hr.
[b] 0.505 in. diameter specimen.
[c] 0.750 in. diameter specimen.

X. The Stress Corrosion Behavior of Maraging Steel Welds

Maraging steels are susceptible to stress corrosion cracking (SCC) in aqueous solutions although 18% Ni grades have been reported to exhibit longer times to failure than other steels of similar strength.[108,109] Welds have less SCC resistance than wrought plates of the same composition. The difference is shown in Fig. 63. This figure also shows that cracking resistance increases as strength decreases. The high K_{Iscc} values measured for steels with yield strengths of approximately 200 ksi and below indicate substantial resistance to stress corrosion cracking. U-bends of 18Ni (180) and 18Ni (200) base plates are uncracked after exposure in sea water for over three years.

Attempts to cathodically protect maraging steel welds in sea water with an impressed current or by coupling them to zinc resulted in a substantial lowering of the K_{Iscc} value (Fig. 64). This is in contrast to the behavior of 18Ni (200) plate for example, the K_{Iscc} of which was reduced only slightly by coupling to zinc. Since the compositions of welds and plates are the same, the difference in their behavior must be associated with differences in the wrought structures of the plates and the cast structures of the welds. Some observations on the influence of structure bn the stress corrosion behavior of welds are given in ref. 110 which also contains a more extensive discussion of the stress corrosion behavior of maraging steels.

X1. Summary and Future Trends

Areas of Application

The development and use of the maraging steels in their early days was fostered in a large part by the interest of the aircraft and aerospace industry. Much of this interest was sparked by the urgent need for materials suitable for solid-propellant rocket motor cases, and these alloys, combining fracture toughness with high strength and excellent fabricability, were timely. Motor cases and other pressurized containers, in a variety of sizes, have since been produced.

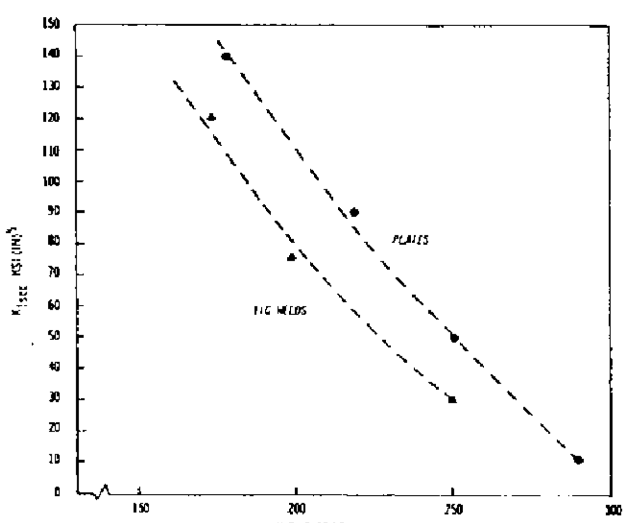


Fig. 63–Effect of yield strength on K_{Iscc} of maraging steel plates and welds

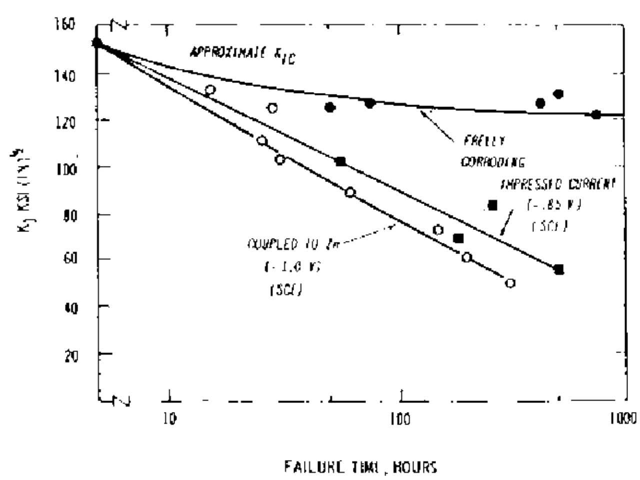


Fig. 64–Effect of cathodic protection on the K_{Iscc} of 18Ni 180 TIG welds in sea water

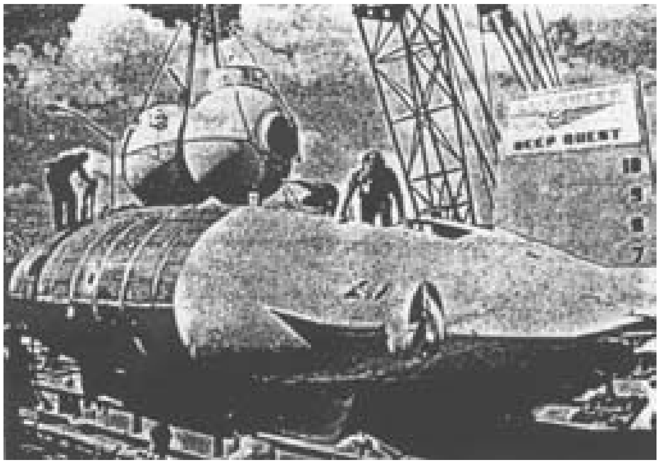


Fig. 65–Twin pressure hulls of 18% Ni maraging steel being lowered into the outer hull of Deep Quest

The ready weldability of the alloys has been an important factor in their selection for other structural applications as well, many in the aircraft and aerospace field. These include flexible shafting; e.g., for a main helicopter rotor drive, wing hinges on sweptwing fighter planes, components of a Canadian Navy hydrofoil ship, and flexural pivots for gimbaling rocket engines.[111]

There has also been some interest in these materials for hydrospace applications. The need for more mobile equipment capable of carrying useful payloads to greater depths again demands materials with a high strength-to-weight ratio, good fracture toughness, ease of welding, and, in this case, resistance to corrosion. Deep Quest (Fig. 65), a vehicle designed as a deep submergence test and oceanographic research facility, has completed dives to 6000 ft, and has been pressure-tested for safe operation to 8000 ft.[112]

The alloys are also finding increased useage in tooling applications[111]; e.g., die casting dies, plastic transfer molds, and extrusion tools. The weldability of maraging steels in these applications is an important advantage, since components made from them can be readily repair welded to extend their useful life.

To date, most of the applications for welded maraging steel have specified the 18% nickel 200 or 250 ksi grades, but there has been some useage of the 300 ksi material as well.

Process Applicability

The bulk of maraging steel weld fabrication has been accomplished by inert-gas processes, particularly gas tungsten-arc. Filler wires and welding techniques are established, and sound, crack-free joints are easily produced. Weldments are characterized by high joint efficiencies and notch properties, with gas tungsten-arc weld toughness approaching that of the parent alloy.

The flux-shielded processes; i.e., shielded metal-arc, submerged-arc, and electroslag, are at an earlier stage of development. The processes are capable of producing joints with high efficiency, but weld ductility and toughness are substantially lower than attainable in inert-gas welds, and cracking has often been observed, especially in submerged-arc weldments. This "state of the art" is common to steels over about 150 ksi yield strength.

Electron beam welding techniques have been developed, particularly for the thinner gauges, and the process is being used for producing a variety of components. The very close fit-ups required to assure satisfactory joints are a disadvantage.

Other joining methods, including flash-butt welding, resistance spot welding, high-frequency resistance welding, inertia welding, and brazing have all been explored but not used widely.

Future Trends

The desirable levels and combinations of properties that can be achieved by solid solution strengthening and age hardening a very low carbon martensite promise well for the future of maraging steels. Some developments are already well underway and others are planned. Figure 66 presents the area of current and future development activity diagramatically and Fig. 67 predicts anticipated strength-toughness combinations.[2]

In the short-term, it is logical to expect expanded

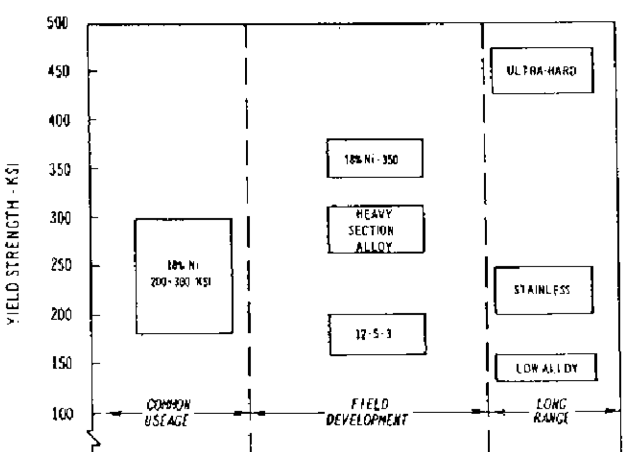


Fig. 66–Maraging steel development

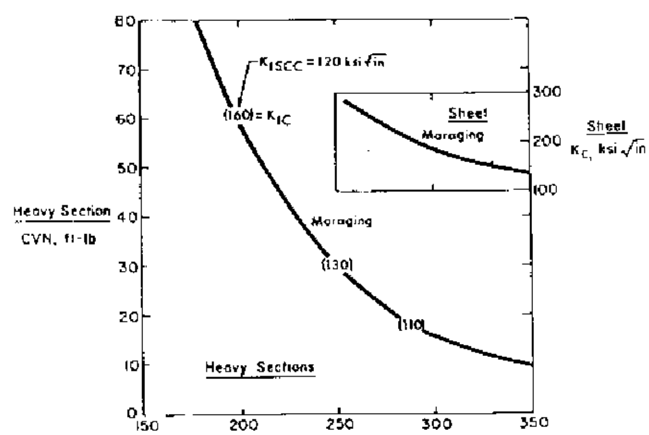


Fig. 67–Predictions of heavy section and sheet properties (based on better lab and commercial results to date)

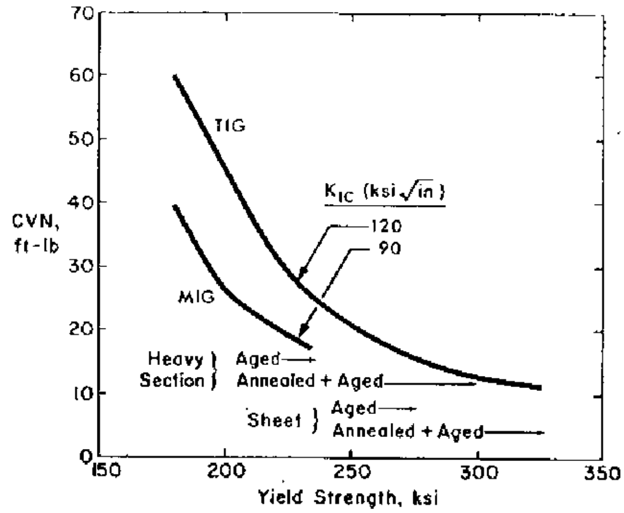


Fig. 68–Prediction of weld properties (based on better lab and commercial results to date)

useage of these alloys now under field development. At around 180 ksi yield strength the 12-5-3 alloy provides high toughness in heavy sections, and has been successfully welded in sections up to 2 in. thick. At around 280 ksi yield strength, short range activity is concentrating on a material with improved toughness in heavy sections In laboratory tests, a 280 ksi alloy, containing higher cobalt, and lower levels of molybdenum and titanium has exhibited weldability similar to the more common 18% nickel grades. At a still higher level, the 18Ni (350) alloy has reached the production stage and has shown promise for a variety of tooling applications. There has also been some interest in this alloy for sheet applications, and it has been successfully welded in this form.

In the longer term, there are several areas of alloy development which may become important for welded applications. These include a lower alloy grade at a yield strength around 150 ksi, a higher strength stainless maraging steel, and ultra hard alloys with strengths over 400 ksi.

Welding technology is expected to keep pace with the growth of applications for both the current and newer grades, and as new alloys develop. Efforts to improve the strength and toughness of welds will continue, and predictions of property levels are shown in Fig. 68.[2] The inert-gas processes, which .have been used so successfully, will undoubtedly remain the prime joining methods, but electron beam welding will also be used extensively. Where it is applicable, inertia welding provides excellent properties and is expected to be used more widely. The inherent difficulties associated with the fluxshielded processes, particularly those that depend upon the use of high heat inputs, will continue to limit the use of these techniques, but some application of shielded metal-arc for welding the lower-strength alloys is anticipated.

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A number of the figures used were taken from the published reports of other workers. We hope that in trying to acknowledge the source of each of these figures in the report, we have always made it clear where the credit belongs.

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