Welding of a High Strength Stainless Steel—IN-744

Welds with a 70,000 psi yield strength are obtained in a steel containing 26% Cr and 6.5% Ni when using commercial welding processes and either a filler metal of the base metal composition or Type 312 stainless steel

BY W. A. PETERSEN AND F. H. LANG

ABSTRACT. As a result of a study of superplastic behavior in Fe-Ni-Cr alloys, a high strength stainless steel was developed containing 26% chromium and 6.5% nickel. The alloy was about twice the yield strength of common annealed stainless steels, offers unique processing advantages and is weldable by conventional techniques. This paper summarizes the general welding characteristics of the alloy and demonstrates the utility of welded joints.

Sound welds in sections as thick as 1 in. were made with conventional welding processes using filler metal with the same composition as the base metal. Welded joints had yield strengths in excess of 70,000 psi without requiring postweld heat treatment and good toughness at ambient temperatures. The corrosion resistance of welded panels was determined during atmospheric exposure and in tests in aqueous corrosive environments. There was no evidence of preferential attack of the weld or heat-affected zone in these tests. Attempts to induce superplastic behavior within the weld and heat-affected zone met with only limited success.

Introduction

An investigation of superplasticity in nickel-iron-chromium alloys led to the development of a high strength stainless steel.[1] This material, IN-744, contains about 26% chromium and 6.5% nickel with the balance essentially iron. In addition to being corrosion resistant, the alloy has a yield strength above 70,000 psi in the annealed condition, good ductility, useful toughness at ambient temperatures and a fatigue life of 10^8 cycles at 60,000 psi (R. R. Moore).

The alloy offers distinct advantages during hot working and should be amenable to unique processing techniques because of the extended deformation capabilities implied by superplasticity. Superplasticity is defined as a condition whereby unusually large elongations are attained in metals and alloys under uniaxial stress at moderately high rates of deformation.[1, 2] The microstructure of IN-744 is characterized by an ultra fine grain size and two-phase structure (austenite in a ferritic matrix) which imparts the superplastic property at temperatures in the vicinity of 1700°F.

The weldability of alloys representative of the IN-744 composition were studied as part of a developmental team effort in order to assure this property in the final alloy. This paper summarizes the general welding characteristics of the alloy and describes the properties of welded joints.

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Table 1—Typical Composition of IN-744 Stainless Steel, Wt-%

C	Mn	Si	Ni	Cr	Ti	P	S	Fe
.03	.3	.4	6.5	26.0	.20	.010	.010	Bal

Experimental Procedure

Plate and sheet for welding tests were worked from small 30 lb laboratory heats and commercial melts as large as 50 tons. The compositions of the plate and sheet used in this investigation were similar to the typical composition shown in Table 1. Matching composition and Type 312 stainless steel filler metals were used for the welded joints.

Laboratory heats were melted in a 50 kw air induction furnace. Electrolytic iron, nickel, chromium, and carbon were charged in a magnesia crucible. The charge was heated to melting and refined with manganese and silicon additions. At 2800° F, titanium was plunged below the surface of the melt. Thirty pound heats were poured in cast iron molds with ceramic hot tops. The ingots were scalped and hot worked at 2200° F from 4 in. square to 2 in. square. They were then reheated at 1700° F, within the superplastic temperature range, and further reduced to either $^1/_2$ in. thick plate or $^5/_8$ in. square rod. The rod and some of the plate were cold worked to wire or sheet form for welding tests. Plate and sheet were annealed at 1700° F for 1 hr and air cooled prior to welding.

Plate was generally bevelled to provide 60 deg vee butt joints for welding tests. Sheet was prepared for welding with the 60 deg vee or a square butt preparation. In order to examine the response of IN-744 experimental filler metals under conditions of heavy restraint, the X-weld test[3] and 1 in. thick single U butt joints were used.

Table 2—Typical Welding Conditions for Joints in Sheet and Plate

Welding process	Thickness, in.	Joint preparation	No. of passes	Volts	Amperes	Travel speed, ipm
Automatic gas tungsten-arc	.020[a]	Square butt	1	12	60	15
Automatic gas tungsten-arc	.060	Square butt	1	8	80	10
Automatic gas tungsten-arc	.125	Square butt	1	11	235	8
Automatic gas tungsten-arc	.140	Square butt	1	12	250	8
Manual gas tungsten-arc	.5	60 deg vee butt	8	17	210	—
Manual covered electrode	.140	Square butt	2[b]	24	90	—
Manual covered electrode	.5	60 deg vee butt	10[c]	26	130	—
Automatic gas metal-arc	.5, 1.0	60 deg vee butt	3, 10	33	315	12
Submerged-arc	.5	Square butt	2	32	600	25

[a] Heavy copper chills were used and consequently conditions are artificial.
[b] $^1/_8$ in. diameter electrode.
[c] $^5/_{32}$ in. diameter electrode.

Fig. 1—Microstructure of gas metal-arc weld made with a commercial Type 312 stainless steel filler metal. The matrix is ferritic with austenite precipitated randomly and at grain boundaries. Weld solidification cracks were intergranular. Etchant: electrolytic 10% oxalic acid. X100 (reduced 22% on reproduction)

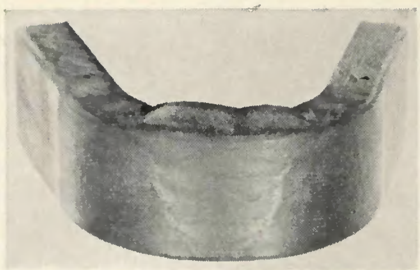

Fig. 2—Weld soundness under severe conditions is shown by this defect-free transverse slice from a 1 in. thick gas metal-arc weld after bending 180 deg

The welding conditions for these joints are summarized in Table 2. The welds were made with commonly used processes and included gas tungsten-arc, gas metal-arc, covered electrode, and submerged-arc. All joints were severely restrained to 2 in. thick copper-faced steel platens.

Completed joints were radiographically inspected for soundness. Plate welds were cut into transverse slices, polished, etched, and examined for defects with a low power microscope. Sound slices were machined into conventional tensile, Charpy V-notch, and R. R. Moore rotating beam fatigue specimens and tested conventionally.

An indication of heat-affected zone soundness was attained during examination of weld slices, but hot ductility tests were also conducted in a Gleeble testing device. The ductility response during the heating portion of the simulated weld thermal cycle was compared to the response during the cooling portion of the cycle.

Panels containing IN-744 and Type 312 stainless steel filler metals were prepared for corrosion tests. Atmospheric exposure was examined in the 800 ft lot at the Francis L. LaQue Corrosion Laboratory, Wrightsville Beach, North Carolina. Corrosion resistance in aqueous acid solution was examined in our laboratory.

Table 3—Mechanical Properties of Welded Joints in 1/2 in. Thick IN-744 Plate

Weld no.	Filler metal type	No. of passes	0.2% YS[a], ksi	UTS[a], ksi	Elongation in 1 in., %	RA[a], %	Charpy V-notch toughness, ft-lb at 70°	0°	−50°	−100°
Gas tungsten arc:										
1	IN-744	12	82.1	89.9	25.0	57.0	66	45	31	17
Covered electrode:										
2	IN-744	10	78.0	102.3	28.0	45.2	48	42	20	13
3	E312-15	6	77.5	101.7	21.5	52.8	24	18	13	12
Gas metal-arc:										
4	IN-744	4	80.8	98.9	20.0	49.2	41	51	19	12
5(1)	IN-744	10	85.0	104.2	25.5	52.2				
6(2)	ER-312	3	80.1	103.9	24.3	57.7	38	18	12	6
Submerged-arc										
7	IN-744	2	77.4	97.9	24.0	46.0	89	34	32	12

[a] YS—yield strength; UTS—ultimate tensile strength; RA—reduction in area.
[b] Joint in 1" thick plate.
[c] Weld solidification cracking was observed in several of the slices cut from this joint.

Table 4—Tensile Properties of Gas Tungsten-Arc Welds in IN-744 Sheet Made with IN-744 and Type 312 Stainless Steel Filler Metals

Weld no.	Filler metal	Joint design	Thickness, in.	No. of passes	0.2% YS[a], ksi	UTS[a], ksi	Elongation in 1 in., %	Elongation in 2 in., %
8	IN-744	Square butt	.140	1	80.5	97.1	18.0	11.3
9	ER-312	Square butt	.140	1	84.1	100.7	18.7	13.5
10	IN-744	Square butt	.090	1	87.5	98.8	14.5	
11	ER-312	Square butt	.090	1	88.5	101.6	12.5	
12	IN-744	60 deg vee butt	.090	2	83.2	94.8	11.0	
13	ER-312	60 deg vee butt	.090	2	81.7	91.6	12.0	
14	IN-744	Square butt	.060	1	82.9	94.3		5.0[b]
15	IN-744	Bead-on-plate	.020	1	85.6	92.9		2.0[b]

[a] YS—yield strength; UTS—ultimate tensile sterngth.
[b] Sheet had yield strength above 100,000 psi, yielding and fracture occurred in weld.

Results

Weld Soundness

The initial welds in this program were made with commercial Type 312 stainless steel filler metals (29% Cr–9% Ni). This filler metal was chosen because of the similarity of its composition to that of IN-744 and the known high strength of welds made with this alloy. Sound joints were made in 1/2 in. thick plate using the manual gas tungsten-arc and covered electrode processes. Also, sound X-weld crack tests were made with these processes and filler metal. Gas metal-arc welds made with Type 312 stainless steel filler metal, however, showed the need for a better material for welding IN-744. Weld solidification cracking was observed in some areas of these welds as shown in Fig. 1.

Welds made with exactly matching composition filler metal within the composition range established for IN-744 were successfully used to produce sound joints in sheet and plate thickness. The joints were made with manual and automatic gas tungsten-arc, gas metal-arc, covered electrode, and

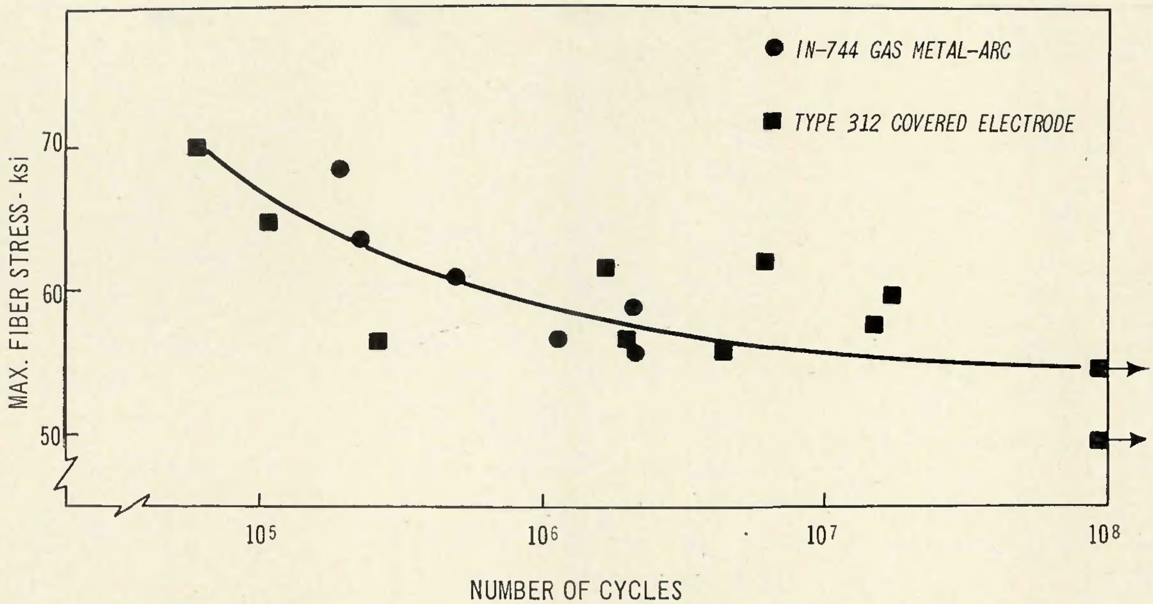

Fig. 3—R. R. Moore fatigue test results on smooth bars containing welds at centers made with filler metals and processes shown

the submerged-arc welding processes.

Transverse slices from the heavier welds could be bent around pins having a diameter equal to four times the thickness without cracking. Weld quality is demonstrated by the bend slice shown in Fig. 2. This joint was made using the gas metal-arc process in 1 in. thick plate under conditions imposing severe restraint. The bent surface shows the cracking resistance of weld, heat-affected zone, and base metal to this test.

Mechanical Properties of Welded Joints

Table 3 summarizes some of the results of tensile and Charpy impact tests on joints in $^{1}/_{2}$ in. thick plate welded with the gas tungsten-arc, covered electrode, gas metal-arc, and submerged-arc processes using both IN-744 and Type 312 stainless steel filler metals. Yield strengths in excess of 75,000 psi and good ductility were observed in all joints. Fracture location showed no preference for base metal, heat-affected zone or weld deposit. The toughness of weld deposits made with IN-744 and Type 312 stainless steel filler metals was found to be acceptable for most anticipated applications at temperatures down to −50° F. Welds made with the IN-744 filler metal offer somewhat greater toughness than those made with Type 312 stainless steel.

The tensile properties of sheet welds made with matching and Type 312 stainless steel filler metals are shown in Table 4. Irrespective of sheet thickness and filler metal, the joints exhibited yield strengths in excess of 70,000 psi. The elongation values in thinner sheet reflect residual warm work and a finer grain size and consequently somewhat higher strength, resulting in local necking with ductile fracture in the weld area. Although these test coupons showed somewhat low elongation values, suitable ductility was obvious in the weld area.

The run-out stress in R. R. Moore fatigue tests of smooth bars was 55,000 psi for welds made with matching composition and Type 312 stainless steel filler metals—Fig. 3. This compares favorably with the run-out stress of 62,000 psi observed for unwelded IN-744. This stress level is considerably higher than that found in other wrought ferritic or austenitic stainless steels.[4]

Hot Ductility Tests

Two heats of the IN-744 composition were subjected to hot ductility tests in the Gleeble. The heats contained normal and high levels of the elements phosphorus and sulfur. The response on-cooling from the nil-ductility temperature was essentially the same as the response found during the on-heating portion of the cycle—Fig. 4. The ductility values were generally high and probably reflect the superplastic behavior of the material in the 1600 to 2000° F temperature range. There was no indication of liquation in either of the heats tested.

These results, together with the

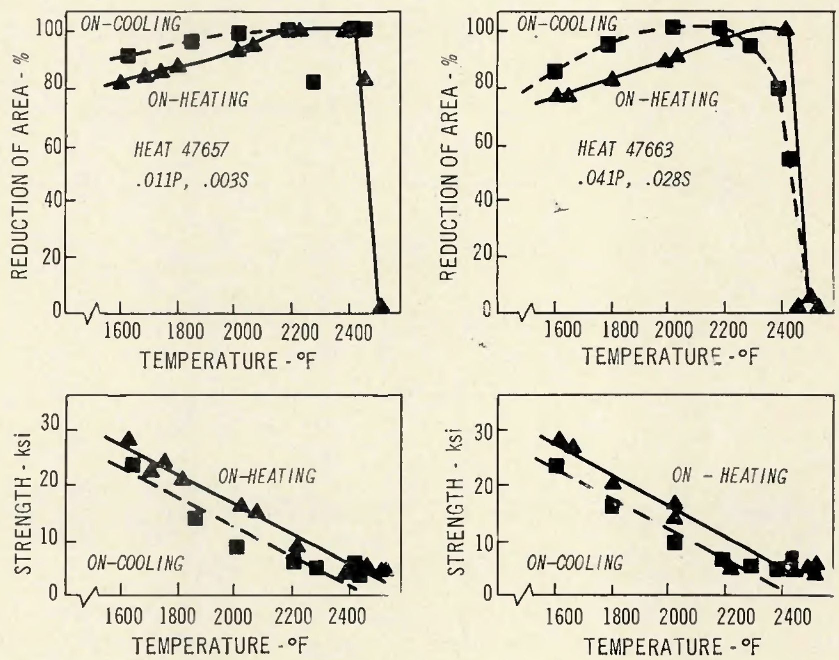

Fig. 4—Hot ductility behavior of two heats of IN-744 containing low and high levels of phosphorus and sulfur

Table 5—Exposure of Welded Samples in Various Aqueous Corrosive Environments

Material	Welded	Corrosion Rate for five 48 hour periods, in./month Boiling 50% nitric acid	Boiling 65% nitric acid	Boiling 10% oxalic acid
IN-744	Yes	.0001	.0003	.0000
IN-744	No	.0001	.0003	.0000
304	Yes	.0003	.0009	—
304	No	.0002	.0009	.0020
310	Yes	.0002	.0003	—
310	No	.0001	.0002	.0008

findings on actual welded joints, suggest that problems with heat-affected zone deterioration would not normally be anticipated in IN-744.

Corrosion Resistance of Welded Panels

Atmospheric exposure of welded IN-744 panels at the 800 ft lot of the Francis L. LaQue Corrosion Laboratory at Kure Beach, N.C. suggest that this alloy has atmospheric corrosion resistance somewhat better than Type 430 stainless steel. After a 9 months exposure period, panels welded with exactly matching composition and Type 312 stainless steel filler metals exhibited less than 10% rust staining. There was no preferential corrosion of the weld or heat-affected zone in this test. On the other hand, however, there is limited evidence that with an unfavorable compositional balance (one resulting in a fully ferritic heat-affected zone) some localized heat-affected zone attack might be expected.

Table 5 gives the corrosion rates for welded IN-744, Type 304, and Type 310 stainless steel in various aqueous corrosive environments. IN-744 exhibited corrosion resistance somewhat superior to that observed in the other stainless steels.

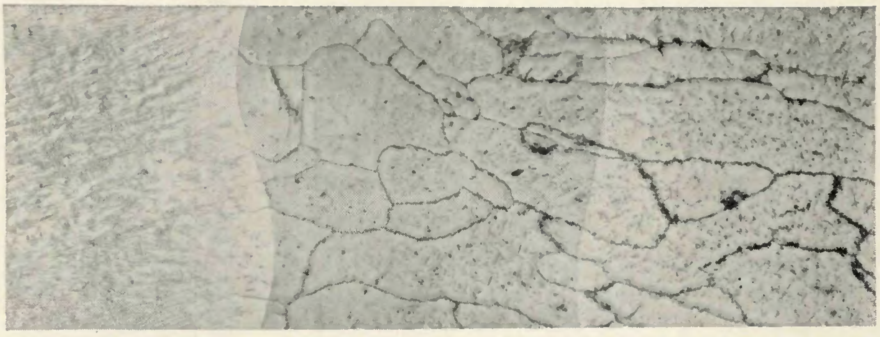

Fig. 5—Composite picture showing the base, heat-affected zone, and weld deposit in a gas metal-arc weld in IN-744. Etchant: electrolytic 10% oxalic acid. X75 (reduced 55% on reproduction)

Superplasticity in Welded Joints

For a metal to exhibit superplasticity it must have an extremely fine grain size. The annealed base metal shown at the left in Fig. 5 meets this criterion; however, the heat-affected zone and the weld deposit were coarse grained. Thus, as shown in Fig. 6, superplasticity would not be expected to be observed within the weld and portions of the heat-affected zone.

Discussion

It has been shown that IN-744 is readily weldable with matching composition and Type 312 stainless steel filler metals. Sound joints have been made with the IN-744 filler metal in sections as thick as 1 in. under conditions of severe restraint using high deposition rate processes. Welded joints exhibit yield strengths in excess of 70,000 psi and generally equal the annealed yield strength of the base metal. Tensile ductility, resistance to fatigue, and corrosion resistance of welds were equivalent to similar properties in annealed IN-744.

Of the materials available for welding IN-744, it appears that matching composition filler metal is the best choice for a majority of applications. Even though covered electrode welds in plate and gas tungsten-arc welds in sheet made with Type 312 stainless steel filler metals have shown acceptable properties, welds made with this material lack soundness under conditions imposing severe restraint and high deposition rates (e.g., gas metal-

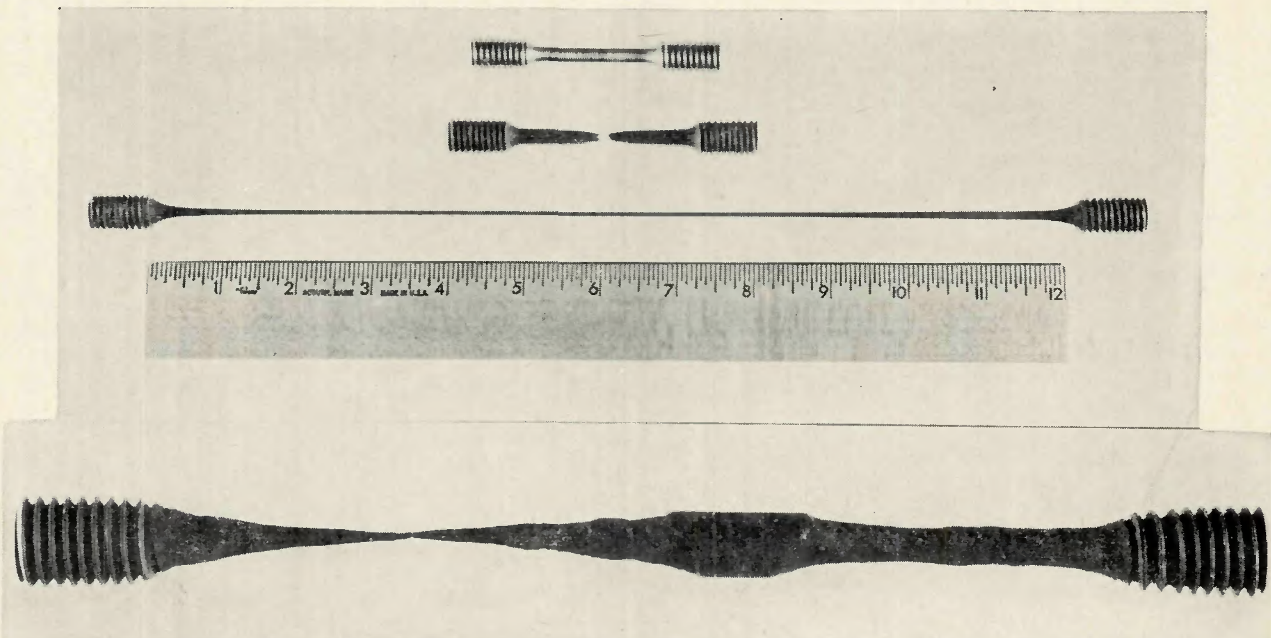

Fig. 6—Superplasticity is characterized by extensive neck free elongation. Top photograph shows machined tensile coupon, a broken non-superplastic coupon, and a coupon which exhibited superplasticity. A tensile coupon containing a weld at its center is shown in the lower photograph

arc process).

Postweld heat treatment is not required to obtain full strength within the weld deposits. In the event that postweld heat treatments were used for any reason, temperatures in the vicinity of 1300° F (sigma formation) and 885° F (885° F embrittlement) should be avoided. Both temperatures increase the strength of the material, but deterioration of notch toughness results.

While it has not yet been possible to induce superplastic behavior in as-welded joints, the idea is provocative since such a result might permit the use of novel fabrication methods.

Conclusions

1. A 26% chromium, 6.5% nickel stainless steel—IN-744—offers a high degree of weldability with common commercial welding processes.

2. Filler metals with compositions the same as the base metal were found to be suitable for welding as was Type 312 stainless steel which is similar in composition.

3. Yield strengths above 70,000 psi and an endurance limit above 50,000 psi were found in welded joints without requiring special techniques or postweld heat treatment.

Acknowledgement

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"Recent Studies of Cracking During Postwelding Heat Treatment of Nickel-Base Alloys"

(1) "Evaluating the Resistance of René 41 to Strain-Age Cracking"

By R. W. Fawley and M. Prager

A procedure for accurately and quantitatively evaluating the resistance of René 41 to strain-age cracking during postwelding heat treatment is reported. The procedure requires only conventional laboratory equipment and welding facilities are not necessary. It is now possible to determine the resistance of heats of René 41 to strain-age cracking prior to their introduction into production lines, and to evaluate the effects of material and process variables on strain-age cracking.

(2) "Variables Influencing the Strain-Age Cracking and Mechanical Properties of René 41 and Related Alloys"

By J. B. Carlton and M. Prager

The problem of strain-age cracking has always been a source of concern to fabricators of welded components of René 41 and other precipitation hardenable nickel-base alloys. A recent study has demonstrated that when argon is substituted for air as the postwelding heat treating atmosphere, cracking of weld circle-patch specimens is eliminated. The same beneficial effects of argon also have been demonstrated in the heat treatment of production welds in rocket engine components.

To explain this behavior a study of the mechanical properties of René 41 was carried out using air, argon, and other test atmospheres. At the same time a large number of heats were studied so that some conclusions might be drawn regarding the importance of composition and microstructure to strain-age cracking. Tests on Inconel 718, Inconel X-750, Waspaloy, and Udimet 500 are also reported to indicate the scope of the environmental effects.

(3) "A Mechanism for Cracking During Postwelding Heat Treatment of Nickel-Base Alloys"

By Martin Prager and George Sines

A mechanism is proposed for the cracking during postwelding heat treatment of precipitation hardenable nickel-base alloys. The conditions under which oxygen may play an active role in promoting crack initiation and growth and the susceptibility of some nickel-base alloys to embrittlement are explained.

It is proposed that precipitation hardenable nickel-base alloys display brittle behavior when dislocations move in a planar manner and pile up at grain boundaries and other barriers to their motion.

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