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REPORT ON THE FOURTH MARAGING-
STEEL PROJECT REVIEW

DEFENSE METALS INFORMATION CENTER
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Director

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REPORT ON THE FOURTH MARAGING-STEEL PROJECT REVIEW

A. M. Hall and J. E. Campbell*

INTRODUCTION

This is a summary of the Fourth Maraging-Steel Project Review which was held on June 9 to 11, 1964, at the Biltmore Hotel in Dayton, Ohio. The Third Maraging-Steel Project Review was held on July 24 and 25, 1963, and is summarized in Defense Metals Information Center Memorandum 181. The complete reports which were presented at the earlier meeting appear in Technical Documentary Report No. RTD-TDR-63-4048, "Third Maraging-Steel Project Review", November, 1963, Air Force Materials Laboratory, Research Technology Division, Wright-Patterson Air Force Base, Ohio.

This fourth meeting was sponsored by the Materials Engineering Branch, Materials Applications Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base. As for the previous meeting, Lt. R. M. Dunco was chairman.

During the past year, considerable effort has been expended to resolve certain technical problems relating primarily to 18 per cent nickel maraging-steel plate which has been under consideration for large booster cases. Among these problems have been banding and the resultant low mechanical properties in the short-transverse direction, deviations in material properties associated with mill processing variables, determination of the hardening mechanism and the effects of the various alloying elements, welding of thick sections, and the fracture toughness of weldments. It also was recognized that other high-strength steels are available or are being developed which should be considered for certain solid-propellant motor-case applications.

The results of the research programs presented at this meeting shed much light on the above problems and indicate that considerable progress has been made toward overcoming the production and fabrication problems of the maraging steels and other high-strength steels. In addition, the results of pressure-vessel tests have demonstrated that, with proper control of melting and mill processing, structural design, and fabrication methods, the 18Ni maraging steels can be used successfully for high-performance pressure-vessel applications.

Colonel M. E. Fields, Chief, Manufacturing Technology Division, Air Force Materials Laboratory, presented the introductory remarks and brought into focus the significant areas requiring further attention. During the succeeding five sessions which occupied 2-1/2 days, 21 scheduled and several unscheduled presentations were made by representatives of Government agencies, industrial concerns, and universities. Abstracts of these presentations are included in this memorandum preceded by a summary of the highlights of the various technical developments.

SUMMARY

General Status of Maraging-Steel Technology

Recent progress in evaluating the 18 per cent nickel maraging steels has encompassed many important items such as melting, mill processing, fabrication, welding, heat treating, effect of service environment, and testing, including burst testing of subsize and prototype motor cases. Emphasis has been placed on determining the effects of production and processing variables, and the effect of variations in composition, on the properties of the final product. Many of those who made presentations said, in effect, "because of the influence of variations in melting and mill processing, different heats respond differently to the annealing and aging treatments, as determined by mechanical tests, and as a consequence, each heat should be evaluated individually to determine the optimum heat-treating conditions for it". For some heats and certain products, 1450 F may be the preferred annealing temperature; while under different circumstances, 1600 F may be the preferred annealing temperature. Furthermore, extended exposure at certain elevated temperatures can cause some degree of embrittlement. Temperatures and times for aging to optimum properties also show considerable variation.

As more information is gained on the effects of the important production and processing variables, it should be possible to control these variables with greater success. Thus, in future heats, the scatter in mechanical properties should decrease. However, in the present state of the art, an evaluation of the aging response of the mill products of each heat as well as the effect of different annealing conditions seems to be desirable in establishing the preferred heat treatment for these products. Heating and cooling rates of the specimens should duplicate those encountered in making the product, if proper account is to be taken of any tendencies toward embrittlement.

Information is steadily being gained on the relationship between properties and metallographic structure in the maraging steels. This information is helping to provide an understanding of the hardening reaction as well as the effects of overaging, grain size, etc. Metallographic examinations at high magnifications also are helping to explain why close control of the many processing variables is required to achieve optimum mechanical properties.

Experience in processing, inspection, fabrication, and welding is uncovering ways of reducing or avoiding problems from banding, low ductility in the transverse direction, and weld cracking in thick sections. Hydroburst tests on various sizes of vessels fabricated from sheet and plate have indicated that with the proper process control and inspection, the burst stress will represent a substantial biaxial gain over the uniaxial ultimate strength of the material. Even though the maraging steels have better fracture toughness and seem to have less tendency toward stress-corrosion cracking than low-alloy steels at comparable strength levels, thorough inspection for flaws in pressure vessels and prevention of exposure to corrosive environments are precautions that cannot be overlooked in the successful application of the maraging steels.

Up to the present time, there has been more development on maraging-steel sheet than plate and even less on large forgings. However, the most recent information regarding processing and properties

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of plate indicates that the mysteries of maraging-steel plate are being solved. Current studies on ring-rolled forgings and other types of large forgings also are yielding considerable information on these products.

Melting and Mill Processing

As noted above, the effects of mill processing variables on the properties of maraging steels have been given considerable attention by many of those who presented papers at this conference. Several authors dealt with the properties of air-melted and consumable-electrode vacuum-arc remelted material. For certain critical applications, some prefer the vacuum-arc remelted material, while others have specified air-melted material for equally critical applications.

Initial hot working of the ingots was reported to have a marked effect on the short-transverse properties of thick plate. Initial reduction by forging as compared with breakdown by rolling appeared to result in improved short-transverse strength and ductility. Poor mechanical properties in the short-transverse direction are usually associated with banding in the structure. This condition has been one of the major problems with maraging-steel plate. However, much has been learned about mill processing techniques that can be employed to minimize this problem.

The effect of finish-rolling temperature also has been investigated. There seems to be agreement among several of the authors that if the final reductions during hot rolling are accomplished with the plate at temperatures below 1700 F and near 1500 F, one will obtain optimum properties in the plate. If the finishing temperature is below 1700 F, one investigator has found that an annealing temperature of 1400 F rather than 1500 F will result in higher strengths after comparable aging treatments. In another report, it was pointed out that prolonged exposure at 1400 F, after heating at 2200 F, produced a dark-etching material at the prior austenite grain boundaries that caused embrittlement. Another investigator has indicated a preference for an annealing temperature of 1600 F to minimize anisotropy. However, these investigators also have evaluated heats that required different treatments to develop optimum properties. Obviously, there is a need for further improvements in the uniformity of melting and mill processing to minimize deviations from the normal expected properties. Until this is accomplished, it appears necessary to check each heat or plate for heat-treating response as well as for degree of banding and fracture toughness in order to be sure of the final properties. One program that was reviewed is specifically intended to investigate the effects of variations in melting and mill processing and to show what procedures are required to develop optimum properties and to do it consistently.

Aging Response

As in previous maraging-steel project reviews, many of the presentations included information on aging response, that is, effects of variations in aging temperature and time at temperature on the tensile and fracture-toughness properties. The results of these studies by the different laboratories showed considerable variation in behavior. In one instance, aging at 950 F for 3 hours resulted in maximum strength with good fracture toughness when the material had been annealed at 1500 F after finish rolling at 1500 F. When annealed at 1400 F, the same material developed optimum properties when aged at 900 F for 3 hours (effects of longer aging times were not studied).

An optimum maraging treatment of 950 F for 3 hours was established for a shear-spun case, but the aging response of the case was somewhat less than for the original ring forging. Apparently, thermo-mechanical treatments employed in fabricating items such as rocket cases can modify both the aging response and the fracture toughness.

Two papers emphasized the effect of prolonged exposure at temperatures below the annealing temperature and above the aging temperature. A 4-hour exposure at 1200 F, for example, converted a large percentage of the metastable austenite to stable austenite. The latter will not transform to martensite on subsequent cooling to room temperature, so the yield strength after the usual aging treatment may be as low as half the expected value. It is important, therefore, to avoid extended exposure in this temperature range, during processing, since this will have a marked detrimental effect on the aging response.

Because of pronounced effects that these processing variables can have on the final properties, several authors indicated that special measures to assure the desired process control are warranted during the processing of maraging steels.

Cold Working

As reported by one author, maraging-steel strip of 250 grade was given a 20 per cent cold reduction followed by aging at 990 F prior to fabrication of spiral-welded pressure vessels. After welding, the vessels were aged at 770 F to strengthen the welds. This combination of cold working and aging apparently provided an optimum balance of properties in the finished vessels since burst tests indicated substantial gains in biaxial stress over uniaxial tensile strength with 100 per cent shear failure. However, other authors have indicated that there is a tendency for cold working to reduce the fracture toughness.

In a report on stress-corrosion testing, it was pointed out that maraging-steel specimens that were cold worked and aged had better stress-corrosion resistance than similar specimens that had not been cold worked.

Welding

According to one report, automatic TIG welding of helically wrapped and welded vessels of maraging steel strip has been developed to the point that fracture during burst testing of these vessels does not occur at the welds.

In one vessel of maraging-steel plate with longitudinal welds, failure was initiated at the longitudinal weld but only after an 11 per cent gain in biaxial stress over the uniaxial tensile strength. The author indicated that this vessel had been repair welded nine times in one location, but failure did not start at this location.

Data also were shown to indicate that the tensile properties of all TIG-weld metal of the 200 and 250 grades of maraging steel approach those of the base plate. However, the fracture toughness of welds of the 200-grade material was substantially greater than that of the 250-grade alloy, according to the author. This is probably one of the major reasons for selecting the lower strength alloy for large thick-wall booster cases.

In another program concerned with welds in plate up to several inches thick, it was reported that sound vertical two-pass welds could be obtained in butt joints of 1.25-inch-thick plate by submerged-arc welding. Thicker plate required more passes. According to this report, problems of restraint-solidification weld-metal cracking, thermal-shock delamination, and cracking in the heat-affected zone had to be overcome. It was also reported that these welds must be very low in hydrogen content (not more than 4 ppm) in order to avoid cracking.

Fracture Toughness

In this conference, as in the previous conference, considerable emphasis was placed on the fracture toughness of the maraging steels. Data presented were for sheet, plate, and welds in plate. Types of specimens used included center-cracked (with cracks through the thickness), shallow-fatigue cracked, and single-edge-notched tensile specimens, notched-and-precracked bend specimens, precracked Charpy specimens, and drop-weight tear specimens. Data were obtained at low and elevated temperatures.

The fracture-toughness properties of the maraging steels are probably more sensitive to melting and processing variables than are the unnotched tensile properties. For this reason, fracture-toughness tests often were used to show the effects of the processing variables noted in the foregoing sections. However, data presented by one investigator often could not be compared with that of another because the importance of various precautions or corrections was not recognized by all of the investigators, or the experimental parameters were not the same. Nevertheless, the significance of fracture-toughness testing in evaluating material for pressure vessels is being recognized. Fracture-toughness requirements for large thick-wall vessels are more critical than for smaller thin-wall vessels. Consequently, the plane-strain fracture-toughness parameters ($\mathcal{G}_{Ic}$ and K_{Ic}) are attracting more interest than the corresponding plane stress parameters ($\mathcal{G}_c$ and K_c).

Since fracture toughness tends to decrease as the strength is increased, a balance between strength and fracture toughness is usually struck in selecting the composition of maraging steel for a given application. In selecting the composition of plate for large motor cases, one contractor has specified 0.05 to 0.25 per cent titanium content with appropriate amounts of the other alloying elements to obtain a yield strength of 200 ksi. When vacuum-arc remelted, this material is expected to have adequate fracture toughness to avoid the problem of premature failures starting at flaws which escape detection by the nondestructive-inspection methods available.

It is generally recognized that in large motor cases, the longitudinal welds are the most critical locations for initiation of failures. For this reason, comprehensive studies of the fracture toughness of welds in plate material have been an important part of the large-motor-case program. Results of these studies are discussed in more detail later. However, it is significant to note that the fracture toughness at the center of TIG, MIG, and short-arc welds was less than that of the base plate and at any of the intermediate zones. Several programs have shown that welds in specimens of maraging-steel plate of 200- to 220-ksi yield strength had substantially higher fracture toughness than welds in plate at the 250-ksi yield-strength level and above. Furthermore, the directionality effects were more pronounced in the weld than in the base plate. These results were obtained on precracked bend specimens with the cracks located in the different zones of the weldment.

In another study, it was shown that shallow-fatigue-cracked specimens having the cracks at the centers of vertical submerged-arc welds had relatively good crack tolerance. These tests were made on 18Ni(250)-grade maraging steel plate.

Studies of fracture toughness of the maraging steels are continuing with particular emphasis being placed on evaluation of welds.

Pressure-Vessel Performance

The ultimate tests of high-strength materials are simulated service tests on fabricated components such as pressure vessels. Burst tests have been made on pressure vessels fabricated from 18 per cent nickel maraging-steel sheet and plate on several of the programs reviewed at the conference. Results of these tests, which are presented in Table 1, indicate a substantial gain in the biaxial burst

TABLE 1. RESULTS OF BURST TESTS OF MARAGING-STEEL PRESSURE VESSELS

Company	Vessel Diameter, inches	Wall Thickness, inch	Yield Strength, ksi	Tensile Strength, ksi	Elongation, per cent	Burst Pressure, psig	Max Wall Stress, ksi	Gain, per cent	Remarks
The Budd Company	6	0.020	-	255	-	--	284	11.4)	Failed in strip, 100 per
(helical weld)	20	0.040	-	269(a)	-	--	293	9.0)	cent shear
	20	0.040	-	297	-	--	326	9.8)	
Curtiss-Wright	40	0.057	284	287	-	1076	375	13.7)	Initial fracture was in
(shear spun)	40	0.057	-	-	-	965	358	-)	longitudinal direction,
									nearly 100 per cent shear
Aerojet-General	36	0.60	226(L)	234(L)	12(L)	8020	238	11	Origin in longitudinal weld
(roll-and-weld)	-	-	241(T)	246(T)	11(T)	--	-	-	
	-	-	208(b)	213(b)	12(b)	--	-	-	

(a) At -65 F.
(b) Welded specimens.

stress over the uniaxial tensile strength. These data are similar to results of other burst tests on maraging-steel pressure vessels. Even though the results indicate satisfactory performance of these vessels, it has been pointed out that for relatively thick-wall vessels, the lower strength maraging grades are preferred over the 300 grade because of better fracture toughness at the lower strength levels.

Properties of Other High-Strength Steels

The last session of the conference was on "Alternate Motor Case Materials". Included in the discussion were such steels as Republic Steel's HP-9-4 series (actually containing about 7.2 per cent nickel, 4.0 per cent cobalt, with chromium, molybdenum, and vanadium, and various carbon contents), HP-150 steel, D6A and D6AC.

One program on the determination of processing procedures for optimum properties of the HP-9-4 series of steels covered effects of deoxidation practice and variations in composition and heat treatment, as these factors affected the properties of sheet and plate products. A presentation on HP-150 steel also described the effects of variations in composition and processing variables.

Two research programs on welding these steels were reviewed. For sheet and plate, TIG welding usually has been the most successful of the methods investigated, but good control of all welding variables is required to develop optimum mechanical properties in the weldment. Joint efficiencies of 95 to 100 per cent were often reported. Under certain conditions, such joint efficiencies can be achieved on the HP-9-4-25 steel when welded after heat treatment without preheating or postheating the weld. High joint efficiency and good toughness also can be obtained in welds of HP-150 steel preheat treated to about 155,000-psi yield strength. For welding of HP-150 steel, a local preheat of about 300 F is recommended.

One presentation covered the fracture toughness of a series of high-strength steels and welds in these steels. From this presentation, it appeared that a balance of good toughness and strength can be obtained in the HY-150, HP-9-4, and 18Ni(200) steels in both the base metal and in welds in the 150,000 to 200,000-psi yield-strength range. The significance of fracture-toughness criteria in predicting the performance of pressure vessels was discussed as well as a procedure for predicting fatigue-crack growth in pressure vessels and estimating minimum service life.

ABSTRACTS OF PRESENTATIONS

Official Welcome

Colonel M. E. Fields, Chief
Manufacturing Technology Division
Air Force Materials Laboratory

Colonel Fields briefly reviewed the background of the high-nickel maraging steels, directing attention specifically to the 18 per cent nickel types. Among the attractive features of these steels are their exceptionally high strength and fracture toughness, their capability to be hardened by means of a simple heat treatment which is carried out at a moderate temperature, their good weldability wherein no preheat nor postheat is required, and their excellent dimensional stability. Current research studies indicate that these steels are hardened by precipitation of Ni_3Mo and Ni_3Ti.

Because of their desirable properties, the high nickel maraging steels are good candidates for large booster cases and high-strength airframe components. In fact, the commercial development of several 18 per cent nickel maraging steels, covering the yield-strength range of 200 to 280 ksi, is well advanced.

The major problems associated with these steels are banded microstructure and comparatively low fracture toughness of welds. Banding is apt to lead to failure by delamination of the material along prominent bands. Low fracture toughness of welds means that the critical crack size to initiate brittle failure is considerably smaller in welds than in base metal.

Session I - Mechanical Properties of Maraging Steels

Effect of Mechanical and Thermal Processing on Structure and Properties of 18Ni-Co-Mo Maraging Steel
by V. H. Thevenow, G. L. Vonnegut, and G. R. Sippel, Allison Division, General Motors Corporation

This presentation covered an investigation of the effect of certain processing variables on the uniaxial tensile properties, the notch strength as determined from part-through fatigue-cracked sheet tensile specimens, and the microstructure of two heats of 18Ni(250) steel plate, three heats of 18Ni(300) steel plate, and one heat of 18Ni(300) steel ring-rolled forgings. All of these materials were produced by the consumable-electrode vacuum-arc remelting process. Most of the samples were in the form of light plate 0.250- to 0.375-inch thick. The processing variables studied were hot-rolling temperature, degree of reduction, per cent reduction per pass, annealing temperature, and aging temperature.

The investigation was prompted by the observation of wide variations in the fracture toughness and uniaxial strength of mill products of apparently similar chemical composition, but processed in somewhat different ways. While a substantial amount of work has been done on annealing and aging, the authors considered that data on the influence of processing variables on these properties are quite limited.

Rolling in the range of 1700 to 1850 F had little effect on uniaxial strength, but below 1700 F strength increased as rolling temperature decreased. The strength under discussion is that which is developed on subsequent annealing and aging. Rolling temperature seemed to have no effect on fracture toughness.

On annealing in the range of 1400 to 1650 F, it was observed that uniaxial strength increased as annealing temperature was reduced for material rolled 60 per cent. The uniaxial strength of material rolled 30 per cent was not affected by annealing temperature, within this span of temperatures.

Except for one heat of 18Ni(300) steel, varying the annealing temperature had no great effect on fracture toughness. This one heat required a 1700 F anneal to produce high fracture toughness.

There were some indications that reducing the draft per rolling pass tended to reduce uniaxial strength. This may have been due to the increase in total heating time required as the number of passes increased to achieve a given total reduction. Rolling at 1500 F followed by annealing at 1400 or 1500 F caused virtually no anisotropy in mechanical properties.

The generally "best" processing combination was to roll 60 per cent reduction at 1500 F and anneal at 1400 or 1500 F. When material processed this way was aged 3 hours at 850, 900, and 950 F, both uniaxial strength and notch strength varied with aging temperature as well as with annealing temperature. When the five heats were all processed the same way (i.e., 60 per cent reduction at 1500 F, anneal 1 hour at 1400 F, and age 3 hours at 900 F), fairly uniform strength and fracture-toughness properties were obtained in four cases out of the five. As mentioned above, the fifth heat had to be annealed at 1700 F to develop good fracture toughness. As observed with the electron microscope, this heat contained precipitates whose number and size decreased as the annealing temperature was increased. These precipitates disappeared on annealing at 1700 F.

Further studies of microstructure revealed no clear-cut relationship between microstructural features and mechanical properties. For example, neither grain size nor degree of recrystallization seemed to correlate with properties. It was speculated that such elements in the composition as carbon, sulfur, silicon, and manganese may be extremely influential with regard to strength and fracture toughness. For instance, it was thought that the relatively high silicon content of the maverick heat may have made solution reactions sluggish and, in this way, may have accounted for the fact that this heat required a high annealing temperature.

<u>Summary of Maraging-Steel Properties in Thick Sections</u>
by F. A. Heiser, Watervliet Arsenal, presented by V. J. Colangelo, Watervliet Arsenal

An investigation of 18Ni(250) steel as a guntube material for the 1-XM 103-mm howitzer was reported. The finished dimensions of the forged and machined tube were 139-1/2 inches long, tapering from 8-1/4 inches at the breech to 6-3/4 inches at the muzzle. The bore was 3-1/4 inches.

The tube is usually made of a low-alloy steel by the autofrettage process, the resulting yield strength of the material being about 220 ksi. By using the maraging steel, and redesigning the tube on the basis of the higher yield strength of this steel, it was hoped to make a tube of higher quality and to make it more easily. Specifically, it was planned to omit the autofrettage step. Improved dimensional stability was also expected.

A total of three tubes were forged from a 23-inch-diameter vacuum-arc remelted ingot. The tubes were annealed at 1500 F, machined and bored, and then aged 3 hours at 900 F. No distortion was detected on aging.

One of the tubes was sectioned to study its mechanical properties and Charpy V-notch properties. The room-temperature yield strength at 0.1 per cent offset was 241 ksi, while the reduction of area was 24 per cent. A Charpy value of 10.7 ft-lb at -40 F was obtained.

The other two tubes were given firing tests at Aberdeen Proving Grounds. The expected life for a low-alloy steel tube is about 4500 rounds. Firing tests were halted when one tube had gone about 400 rounds and the other about 500 rounds. Cracking and heat checking had appeared quite suddenly and quite early--after only some 50 rounds, in fact. The firing tests were stopped when this condition progressed to the point that the tubes were declared hazardous.

After the firing tests, the properties of the tubes were checked. Yield strength had decreased and reduction of area had increased at both ends. Transverse V-notch Charpy tests remained about the same, 7 to 12 at -40 F. W/A values from precracked Charpy tests were about 415 at the breach end and 315 at the muzzle end.

The tubes were badly eroded and cracked. Some cracks were as deep as 5/16 inch, about 1/4 of the wall thickness. The cracks seemed to follow prior austenite grain boundaries. Light microscopy revealed a coarse grain structure, banding, and three kinds of precipitate one of which was identified as TiC.

<u>Low-Cycle Fatigue Properties of High-Strength Solid-Propellant Rocket Motor Materials</u>
by C. M. Carman and J. M. Katlin, Frankford Arsenal, and P. C. Paris of Lehigh University

This report was directed toward gaining an improved insight into the behavior of subcritical-size defects under repeated loadings. The subject is of importance in the manufacture and evaluation of solid-propellant rocket motor cases made of ultrahigh-strength steels which, by their nature, are sensitive to the presence of defects. Such motor cases are subjected to several cycles of hydrotesting and it is highly desirable to have quantitative information on the growth of these subcritical-size defects, in the steels of interest, under this type of low-cycle fatigue situation. This type of information can be of assistance in developing suitable methods of calculating the life of the case.

The materials studied were 300M, H-11, D6A, and the 18Ni(250) grade of maraging steel. A center-cracked sheet specimen was used for the fatigue tests which were carried out by using two techniques: (1) cycling at a constant value of K by appropriately varying the stress, and (2) cycling at a constant stress and with accompanying variation of K. The constant-K technique was used for evaluating crack growth rates in the high-K-level area (very low cycle, high stress) and the constant-stress technique was used for tests which started in the low-K area (high cycle, low stress). Sufficient overlap was provided in the range where the K levels were similar to insure a smooth transition between the two methods of testing.

When the rate of crack extension for the maraging steel was plotted as a function of K on a log-log chart, it was observed that, within the limited data obtained for this material, the logarithm of the rate of crack extension was a linear function of the logarithm of K for both the constant stress and constant-K experiments. Calculation of the slope of this line gave a value of 4.

Electron microfractographs were prepared at selected positions along the path of fatigue-crack extension in maraging-steel specimens. These fracture surfaces exhibited fatigue growth rings. Measurement of the spacings of these growth rings would also represent the amount of crack extension per cycle. The rates of crack extension as determined by these two methods were in reasonably close agreement.

When the rates of crack extension as a function of K were plotted on a log-log chart for all the steels tested, it was found that, at the lower values of K (K much less than K_c), the logarithm of the rate of crack extension was a linear function of the logarithm of K. Calculation of the slope of this line again gave a value of 4. Also, the data for all the materials at the lower K values fell into a small scatter band close to the straight line having a slope of 4. This indicates that for the steels studied, the rate of crack propagation was relatively insensitive to alloying, processing, mean load, frequency, etc.

At the very high K levels (K close to K_c), there were departures from the fourth-power relationship to a higher rate of crack propagation. From the experimental observations it appeared that the points of departure occurred at values of cyclic K equal to 0.7 to 0.8 the static K_c value.

The data obtained offer a basis for predicting the low-cycle fatigue behavior of structures fabricated from the 18Ni(250) grade of maraging steel as well as other steels. The data presented indicate that the rate of crack growth is a function of K which, in turn, is a function of crack length, gross section stress, and the geometrical configuration of the crack.

<u>Fracture Toughness and Delayed Failure Behavior of 18 Per Cent Nickel Maraging Steel</u>
by A. W. Brisbane, J. M. Hawn, and R. T. Ault, Air Force Materials Laboratory

The authors consider that, in using steels at ultrahigh strength levels, two of the most important material properties for determining component reliability are resistance to crack propagation (fracture toughness) and resistance to environmentally induced delayed failure. Therefore, the purpose of the investigation reported here was to evaluate an 18Ni(300) steel in the form of 50-mil sheet with respect to these two properties. Of particular interest was the material's resistance to crack propagation in air and water environments as a function of various maraging treatments.

Aging the material at 900 F for 3 hours produced a tensile yield strength of 322 ksi. The material was studied in this condition, as well as at yield-strength levels of 300 ksi and 270 ksi.

Fracture toughness was investigated in terms of K_{Ic} and W/A. The K_{Ic} parameter was determined from center-notched fatigue-cracked sheet tension specimens, using the compliance-gage technique. W/A was determined with precracked Charpy impact specimens. Both parameters were investigated over the temperature range of -100 F to +400 F.

The environmentally induced delayed-failure behavior was investigated through the use of constant load, stress-rupture tests on precracked center-notched tensile specimens. The delayed-failure behavior was investigated as a function of strength level in a distilled-water environment at room temperature.

The yield and ultimate tensile strengths were observed to demonstrate the usual temperature dependence for high-strength steels, showing a gradual increase with decreasing test temperature. The notch tensile strength also showed a similar gradual increase with decreasing test temperature down to room temperature, but then it decreased at -100 F. The plane-strain fracture-toughness values, K_{Ic}, were observed to decrease gradually with decreasing test temperature below 200 F. The K_{Ic} values ranged between 113 ksi $\sqrt{in.}$ at 200 F and 68 ksi $\sqrt{in.}$ at -100 F. The notched strength-yield strength ratios varied from 0.33 to 0.61. Despite these low ratios, the K_{Ic} values indicated that the materials had a reasonable degree of toughness at these high strength levels. For both low-alloy quenched-and-tempered steels, and maraging steels, K_{Ic} increases with increasing notched strength-yield strength ratio. However, for a given value of notched strength-yield strength ratio, the toughness of the maraging steels was about twice as great as that of the low-alloy steels. This emphasized the danger in using the notched strength-yield strength ratio as an index of notch toughness, when comparing different steels.

K_{Ic} was observed to depend on rolling direction, being lower in the transverse than in the longitudinal direction. This parameter also seemed to decrease gradually with increasing strength level; however, the variation in K_{Ic} from heat to heat, for a given strength level, was greater than the change due to strength level. Experiments also indicated that underaging offers a method for increasing fracture toughness and decreasing strength level. The authors suggested that this may be important not only for strength-toughness evaluations of individual plate or sheet material produced with varying mill practices, but also for improving the toughness properties of welded joints.

The effective surface energy for crack propagation, W/A, determined from the precracked Charpy-impact specimens showed trends similar to those for K_{Ic}. This toughness parameter seemed to be more discriminating than K_{Ic}.

Concerning the plane-strain fracture-toughness parameter, K_{Ic}, the questions of when slow crack growth really begins and what conditions govern this initial growth stage were singled out as unanswered questions. Two specific problems are: (1) when several discontinuities in the load-compliance or load-resistance curves ("pop-ins") exist, which one is to be selected for the K_{Ic} measurement, and (2) when no pop-in is observed how can initial slow crack growth be detected? The latter question was of concern because distinct pop-ins were the exception rather than the rule in this study. Experiments indicated that the point of deviation from linearity in the compliance curve does not mark the beginning of slow crack growth.

Delayed failure tests were made on specimens aged at 750, 800, and 900 F. When the specimens were loaded at 90 to 95 per cent of the notch tensile strength, failures occurred within 20 to 30 minutes. At applied stress levels of 40 to 80 per cent of the notch tensile strength, failures occurred in the order of 20 to 30 hours. No failures in 1000 hours were observed at applied stresses less than 40,000 psi. The failure mechanism was believed to be hydrogen embrittlement.

It was of interest to note that, at a given applied stress level, material aged at 750 F failed in the shortest times, while material aged at 900 F failed in the longest times, although the fracture toughness was greatest for the 750 F material and least for the 900 F material.

<u>Structure and Properties of 18Ni Marage Steel</u>
by B. R. Banerjee, J. M. Capenos, and J. J. Hauser, Crucible Steel Company of America

This presentation described a study of the mechanical properties and structure of 18Ni(300) steel sheet rolled from a 2- by 8-inch bar. The latter, in turn, had been produced from a consumable-electrode vacuum-arc remelted ingot.

Annealing at 1400 or 1500 F produced higher strength in subsequently aged material than did annealing at 1600 F and above. No significant differences in strength were noted between material air cooled or ice-brine quenched from the annealing temperature.

Neither strength nor fracture toughness appeared to be influenced by variation of grain size. It was speculated that the prominent subgrain structure in this steel, which seems to control martensite plate size, renders the prior austenite grain size less important than it is in other types of steel.

It was observed that etching with 5 per cent nital or 20 per cent H_2SO_4 in water gave true structures, while the structures revealed by several other etchants were spurious.

No retained austenite was found on air cooling from either 1500 or 2000 F. However, on aging 100 hours at 900 F, after annealing at 1500 F, 1 per cent reverted austenite was found; after 1 hour at 1200 F, the figure was 70 per cent. However, in material annealed at 2000 F, 14 per cent reverted austenite was found after 100 hours at 900 F, and 24 per cent after 500 hours at 900 F.

In terms of both strength and fracture toughness, the optimum aging temperature appeared to be 900 F. Aging 1 hour at this temperature produced a fine general precipitation preferring certain planes within each blocky martensite region. After 10 hours, reverted austenite was seen distinctly at prior austenite grain boundaries. Aging produced dislocation tangles and increased dislocation density, especially at aging temperatures of 800 and 900 F. At 1000 F and higher aging temperatures, there was distinct evidence of precipitate growth indicative of overaging. At 1300 F, re-solution of the precipitates was observed along with rapid reversion to austenite.

Studies to identify the precipitates were carried out by means of extraction replica electron microscopy, electron diffraction of extraction replicas, X-ray analysis of electrolysis residues, and electron-probe microanalysis of extraction replicas. The findings were generally compatible with the hypothesis that the precipitates were Ni_3Mo and Ni_3Ti.

With decreasing test temperature, the uniaxial strength of aged material steadily increased, while fracture toughness decreased from 212 ksi $\sqrt{\text{in.}}$ at room temperature to 50 ksi $\sqrt{\text{in.}}$ at -320 F. The drop in fracture toughness occurred sharply between -100 and -320 F.

Cold rolling after annealing but before aging increased strength somewhat but reduced fracture toughness markedly. The effect of ausworking 50 to 90 per cent at temperatures of 500, 750, and 1100 F was studied. It was observed that 90 per cent reduction was required to improve strength significantly. This treatment drastically reduced fracture toughness.

<u>Session II - General Maraging-Steel Evaluations</u>

<u>Physical-Property Advances in Maraging Steels</u>
by T. J. McCaffrey, Carpenter Steel Company

This was a discussion of improvements which have occurred in the uniformity and reproducibility of the mechanical properties of 18Ni maraging steels resulting from improved production methods. The presentation was based on data from 41 heats. In each heat, a 20-inch-diameter ingot was produced by the vacuum-arc remelting process. In the form of 9- and 12-inch-square forgings, improved elongation and reduction of area at yield strengths in the range of 277 to 281 ksi were reported. Also, it is reported that transverse and longitudinal ductility are much higher and more nearly alike at lower forging reductions. Much of these gains were attributed to better control of chemical composition. Carbons are as low as 0.006, sulfur can be held at 0.004, and titanium maintained in the range of 0.30 to 0.55. Notched strength-to-ultimate strength ratios of 1.0 or greater were reported for plate up to about 0.4-inch thick.

Confirmatory comments were made by Dr. John C. Hamaker, Vanadium Alloys Steel Company. Some 2 years ago, illustrative ductility values for 6- by 6-inch-square 18Ni(300) steel forgings were 7.5 per cent elongation and 33 per cent reduction of area in the transverse direction at the midsection; the corresponding values for the longitudinal direction were 10 per cent and 50 per cent respectively. Currently, in 18-inch-diameter 18Ni(300) forgings longitudinal midradius values are 6.5 per cent and 27 per cent, with corresponding transverse values of 5.5 per cent and 25 per cent. Considering the great increase in the section size of the forgings, these ductility values mark a significant gain.

Stress-Corrosion Cracking of Maraging Steels

Alfred Rubin,
Aerojet-General Corporation

The author pointed out that, while materials for rocket-motor cases must meet requirements with respect to such factors as strength, fabricability, weldability, and fracture toughness, these materials also must possess adequate resistance to stress-corrosion cracking. Without the capability to resist stress-corrosion cracking, the material's usefulness is severely limited because stress-corrosion cracking is catastrophic and occurs at stress levels well below the yield strength.

Accordingly, Aerojet-General undertook a program on this subject. The experimental materials were H-11, D6AC, 18Ni, and 20Ni maraging steels. The 20Ni steel was soon dropped because of its low fracture toughness. Several heats of the 18Ni type, with titanium ranging from 0.2 to 1.0 per cent, were included. These steels were produced by the consumable-electrode vacuum-arc remelting process. The maraging steels were tested as annealed and aged in the standard manner, and also as cold rolled 50 per cent before aging. In addition, welded specimens were included.

The materials were tested in the form of sheet specimens 1-3/4 inches wide, beam loaded to 75 per cent of the yield strength. A center notch was placed in each specimen (by the Elox method), the ends of which were sharpened by tension-tension fatiguing.

Among the environments used, distilled water was found to be the most aggressive, with 3 per cent saline solution next, and tap water least. In aerated distilled water it appeared that, at any given yield strength, H-11 was generally less resistant than annealed-and-aged 18Ni maraging steels, while these in turn were less resistant than cold-worked-and-aged 18Ni maraging steels. Looking at each steel separately, resistance increased as the strength level decreased.

The maraging steels seemed to fail by developing a number of small cracks rather than one large crack. The maraging-steel samples did not fail with a sudden burst as the low-alloy steels did. The cracks tended to progress downward from the tension surface and stop at the neutral axis. Sometimes it seemed that cracking may have been of microscopic size to start with. Therefore, since the cracking was not visible, the steel may have been considered resistant when, in point of fact, it had actually failed. Welded samples failed in the heat-affected zones.

Specimens of maraging steels were exposed to the atmosphere at Kure Beach, North Carolina; Bayonne, New Jersey; and Newport Beach, California. Some failures occurred. Cold-worked material looked best.

In distilled water, the 18Ni steels showed increased susceptibility to cracking as the temperature was increased from 80 to 160 F. The standard quenched-and-tempered steels were not affected by this temperature rise.

Addition of 1/4 per cent sodium dichromate and 4 per cent water-soluble oil effectively inhibited distilled water and no failures of maraging-steel specimens occurred. The place of an inhibitor would be in hydrotesting.

Among coatings studied, zinc-epoxy was ineffective as a protection. Chromate-epoxy was good, while polyurethane was fairly good. The difficulty with coatings, of course, is the danger of breakthroughs and holidays.

In addition, Aerojet-General has tests going on to study the effect of an imposed electrical potential on the resistance of maraging steels to stress-corrosion cracking in 3 per cent saline solution. Early indications are that this galvanic type of protection can be made to work.

Hydrogen Embrittlement of 250-Grade Maraging Steel

by H. C. Tourkakis and C. B. Sonnino,
Washington University, St. Louis, Missouri

This presentation was based on a thesis prepared by H. C. Tourkakis to fulfill requirements for the M. S. degree. The program was carried out under the direction of Dr. Sonnino. The objectives were to study the diffusion of hydrogen into and out of the 18Ni(250) maraging steel, the embrittlement of this steel by hydrogen in a triaxial-stress state, and the embrittlement of this steel under biaxial stress in corrosive environments.

The types of specimen used in the program were smooth sheet-tensile, edge-notched sheet-tensile, and bend test specimens. Hydrogen was introduced by cathodically charging in a 4 per cent H_2SO_4 solution at a current density of 0.5 amp/sq in.

It was noted that, as charging time increased up to 2 hours, notched tensile strength decreased. There was little further decrease with charging times beyond 2 hours. Aging charged specimens at room temperature up to 96 hours prior to tensile testing produced partial recovery of strength. These findings indicated that the steel can be embrittled by hydrogen and suggested that permanent damage to the 18Ni(250) steel can be done by this element.

In 1000-hour sustained-load bend tests in a 100 per cent humid atmosphere, a hydrogen-charging time effect was noted. No failures occurred in specimens charged 1/2 hour, even when loaded to 90 per cent of the yield strength. However, when the charging time was 2 hours, the stress had to be decreased to 70 per cent of yield to avoid failures.

In 1000-hour sustained-load bend tests in a salt fog, specimen behavior after 1/2-hour hydrogen charging followed by 100 hours of aging was erratic. A few specimens survived the 1000-hour period, while several failed after various shorter times in test. On the other hand, all specimens charged 2 hours failed at times usually far short of 1000 hours even when loaded to only 70 per cent of the yield strength.

The fracture surfaces differed in appearance from those of hydrogen-embrittled ultrahigh-strength low-alloy steels. However, the authors considered that the topography of the fractures suggested a type of cleavage mode.

Use of Dual Transducers for Ultrasonic Detection of Laminar Flaws
by S. D. Hart,
U. S. Naval Research Laboratory

An improved system for inspecting material for laminar flaws was described. The method is capable of identifying a 5/64-inch-diameter flat-bottomed hole 0.050 inch below the surface. The usual method cannot pick up flaws closer than 1/8 inch from the surface and, often, 1/4 inch from the surface. Though it does not indicate flaw depth, the NRL system shows the area of the defect quite accurately. Like many other ultrasonic methods, this system detects flaws which are parallel or nearly parallel to the surface. Flaws which are at an angle to the surface and, thus, cannot intercept the ultrasonic wave will be missed.

The improved method uses two transducers. One is a transmitter which sends ultrasonic waves into the material. The other is a receiver. Because the receiver is a separate unit, it can be provided with a sound-absorbent barrier to screen off the strong reflections from the surface of the metal. In this way, its capability to pick up reflections from defect surfaces in the interior is greatly enhanced. It is this arrangement which makes possible the detection of defects much closer to the surface than can be done by standard equipment.

Another feature is the immersion of the system in a medium such as water. A nonimmersed system requires a smooth, clean surface while an immersed system does not need so good a surface.

This improved method was used to inspect the Lockheed 120-inch vessel after the first hydrotest and again after rehydrotesting. The objective was to determine what defects existed in the vessel after the first test and to learn whether any had grown as a result of the second test. Many laminar flaws, larger than the 5/64-inch minimum, were identified in the vessel. However, none appeared to have grown. After the second inspection, the material was sent to Mellon Institute for metallographic examination of the areas where laminar defects were indicated. The correlation was reported to be quite good, except that metallographic scanning found some defects which were tilted and, hence, were not detected by the ultrasonic device.

The author recommended making the type of inspection he described in addition to radiography and shear-wave inspection. He stated that both of the latter types of method may overlook laminations.

Session III - Mechanical Properties of Welds and Fabrication of 18 Per Cent Nickel Maraging Steels

Development and Hydroburst Analysis of an Ultrahigh-Strength Solid-Propellant Rocket Motor Case
by V. Mehra and E. Gilewicz,
Curtiss-Wright Corporation

A program to investigate the capability of the 18Ni(300) type of maraging steel to achieve a minimum biaxial yield strength of 325 ksi, when in the form of a 40-inch-diameter by 0.057-inch-wall vessel, was described in this presentation. The program called for burst testing two 40-inch-diameter vessels. On being hydrotested, the first vessel showed the exceptionally high biaxial ultimate strength of 375 ksi. This is reported to represent an increase of more than 50 per cent over the results achieved with D6AC, the steel currently used for Minuteman cases. The second vessel showed the excellent biaxial ultimate strength of 358 ksi when hydroburst tested.

The steel used was consumable-electrode vacuum-arc remelted material. The end closures were forged. The center body was hydrospun from a machined ring forging. The ring forgings were annealed at 1500 F before machining. Spinning was accomplished in four passes, with an intermediate anneal after the second pass. Welding was done by the TIG process using wire of fairly high titanium content (0.79 per cent) which has been found to reduce porosity and promote high joint efficiency.

Experiments were conducted with specimens cut from a trial center body to optimize the practice for final heat treatment of the finished vessels. Microstructure, smooth-bar tensile properties, and fracture toughness as determined from center-notched tensile specimens, were used as guides. From the results obtained it was decided to use 950 F for 3 hours after a 1-hour anneal at 1500 F.

Details of the burst test of the first vessel were given. It was instrumented with BLH PA-7- and FABX-50-type strain gages. Prior to pressurizing to failure, the vessel was proof tested at 700 psig. To burst the vessel required a pressure of 1076 psig which calculated to a biaxial strength of 375 ksi on a PR/t basis.

On examining the fracture, it was concluded that the failure had a single point of origin and that the vessel underwent considerable plastic deformation in the biaxial stress field prior to fracture. At the origin, the fracture appeared to be almost 100 per cent shear. Preexisting cracks and flaws at the origin were not found. Accordingly, the authors considered that the vessel had not failed prematurely and that the material had exhibited maximum response under the prevailing biaxial-stress state.

Fracture Toughness Evaluation of Welds in Maraging Steel
by H. L. Smith and H. E. Romine,
U. S. Naval Research Laboratory and
U. S. Naval Weapons Laboratory, respectively

This presentation described fracture-toughness evaluations of 3/4-inch-thick 18 per cent nickel maraging-steel base plates and weldments, using a precracked bend specimen for most of the tests. The test materials consisted of air-melted 18Ni(250) steel and vacuum-arc remelted 18Ni(200) steel. However, all data reported relate to the 250 material; results obtained on the 18Ni(200) steel were not available at the time of the meeting. The welding methods were MIG, TIG, and short arc. The weldments were prepared by Excelco Developments, Inc. The influence of rolling direction also was examined.

The regions of weldments which were evaluated included the center, the fusion line, the heat-affected zone not far from the fusion line, and the dark band farther away in the heat-affected zone where austenite reversion had occurred. The method of proceeding was to arrange for the crack in the precracked specimen to terminate in the region of interest. Thus, in some specimens the crack was placed in the center of the weld, in others the crack was in the dark band, and so on.

The values obtained for the fracture toughness (K_{Ic} values) of the weldments were influenced by the rolling direction of the base plate. And, of course, the toughness values obtained for the base plate itself showed directionality effects. For TIG welds, K_{Ic} decreased among the various regions in the following order: fusion line, heat-affected zone, dark band, center of weld. In fact, the K_{Ic} values for the fusion line and the heat-affected zone were higher than those obtained for the base plate. For TIG welds, the K_{Ic} values obtained in the heat-affected zones were significantly greater than those obtained at the center of the weld. For reasons not yet known, the K_{Ic} values obtained in the heat-affected zones of the short-arc welds were exceptionally high; on the other hand, the center of the short-arc welds gave the lowest K_{Ic} values among the weldments investigated. For the same heat of steel and the same direction of crack propagation, the fracture toughness of TIG welds was higher than that of MIG welds in both the heat-affected zone and the center of the weld.

In addition to the tests made on weldments, the effect of water in the fatigue notched bend specimen was briefly examined. Twenty-four-hour sustained load tests at 90 per cent of the fracture stress were carried out using tap water. No failures occurred. When unloaded, dried, and reloaded to failure the specimens fractured at stresses within, or slightly above, the scatter band obtained for specimens tested in air in the standard manner.

The delaminating tendency of the maraging steels, when in the form of plate, prompted determination of tensile properties in the short transverse direction. A spool-shaped specimen was used for tests on 3/4-inch plate. Areas of an 18Ni(250) plate which had delaminated in bend tests gave a tensile strength of 190 ksi and a reduction of area less than 2 per cent. A nondelaminated area gave the full tensile strength of 270 ksi at about 3.5 per cent reduction of area. A region which tended to delaminate in bend tests showed about 250-ksi tensile strength, but no reduction of area, after being soaked at 2100 F and aged. A bend test of this material revealed some tendency to delaminate. Metallographic examination of material treated at 2100 F suggested that austenite banding had disappeared but pronounced clusters of titanium carbonitrides remained.

<u>Isothermal Embrittlement of 18 Per Cent Nickel Maraging Steel</u>
by C. J. Novak,
International Nickel Company, Inc.

An investigation is being undertaken to study embrittlement phonomena that may possibly occur during processing of 18 per cent nickel maraging steels. The bulk of the experimental work done to date has been with specimens from an air-melted 18Ni(250) heat rolled into 5/8-inch-thick plate. However, some confirmatory tests have been made with material representing other 18Ni(250) heats as well as 18Ni(200) heats, both air melts and consumable-electrode vacuum-arc remelts made in commercial equipment and in the laboratory.

The general procedure was to heat specimens 1 hour at 2200 F and then expose them directly at lower temperatures for various periods of time. After exposure, the specimens were water quenched, machined and aged 3 hours at 900 F.

Exposure temperatures of 1200 to 2000 F were used, with time at temperature ranging from a few seconds to 10,000 minutes. Very little embrittlement, as indicated by standard Charpy V-notch tests, occurred at 2000 F, but in the range of 1400 to 1800 F embrittlement was pronounced. Embrittlement was also observed in specimens exposed at intermediate temperatures but not subsequently aged. The data suggested that two embrittling reactions were taking place. One seemed to occur at comparatively high temperatures and the other appeared to occur either during aging or was completed during aging.

Material exposed at an embrittling temperature, such as 1400 F, and then aged at 900 F would become increasingly brittle the longer the time at the aging temperature. Again, embrittlement was induced by slow cooling to room temperature from 2200 F.

Evidence of microstructural changes accompanying embrittlement was reported. Micrographs obtained by light microscopy, electron microscopy, and transmission electron microscopy were presented. They suggested the development of precipitates along the prior austenite grain boundaries.

Continued work on the embrittlement caused by heating in various ways indicated that using more normal temperatures, rather than 2200 F, produced less impairment of toughness. This observation led to the speculation that the large grains developed at 2200 F may have magnified the embrittling effect, since it appeared to be a grain-boundary phenomenon. If so, recrystallization should be beneficial. At the time of the presentation, this study had not been completed. However, the data obtained seemed to suggest that factors other than grain size may be involved.

In experiments to learn whether a simple heat treatment could restore toughness to embrittled material, it was found beneficial to anneal at 2000 F. It was pointed out that this finding related to the particular test material used; another heat with a different history might require a different temperature.

From the work done thus far, it was concluded that the 18 per cent nickel type of maraging steel can be embrittled by interrupting cooling from elevated temperatures and holding at such intermediate temperatures as 1200 to 1800 F. It was also observed that slow cooling through this range could produce embrittlement. The embrittling mechanism is not yet known.

It was recommended that the reheating temperature for final hot working be no higher than 2000 F, that finish-hot-working temperature be as low as practical, that cooling after hot working be rapid, and that annealing conditions should be the minimum for recrystallization.

<u>Evaluation of 18 Per Cent Nickel Maraging Steel</u>
by P. P. Crimmins,
Aerojet-General Corporation

The Aerojet-General program on evaluation of maraging steel plate for the Air Force has been completed and this presentation was a summary of the results obtained. An outline of the tests performed is as follows:

I. Tensile-aging response

II. Fracture-toughness tests

A. Correlation studies

1. Plate-size center-notch specimens
2. Plate-size partial-thickness-crack specimens
3. Slow notch-bend specimens
4. Precracked impact specimens
5. Subscale partial-thickness-crack and slow notch-bend specimens

B. Five-inch-thick plate and 4-inch-square bar

1. Slow notch bend
2. Precracked impact

III. Chemical

IV. Metallurgical.

Results of the aging-response studies were reported at the Third Maraging-Steel Project Review. In the fracture-toughness correlation studies on seven heats of 1/2-inch plate, it was found that there was good correlation between the results for the partial-thickness-cracked specimens and the precracked slow-bend specimens of 250-grade material. From the scatter band of slow notch-bend test data, values for G_{Ic} were over 300 in-lb/in.^{2} for material of 200-ksi yield strength and less than 100 in-lb/in.^{2} for material of 300-ksi yield strength. For the precracked Charpy tests, W/A values for the 200-ksi yield-strength material were substantially higher based on in-lb/in.^{2} units than corresponding values obtained from the bend tests. However, for the 300-ksi yield-strength material, the precracked Charpy data were in the same range as the bend-test data.

Based on data for longitudinal specimens from 23 heats which were given the standard annealing treatment and aged at 900 F for 4 hours, the effect of composition on the yield strength could be described by the following equation:

$$\text{Yield strength, ksi} = 38.1 + 8.8\ (\%\ Co) + 22.6\ (\%\ Mo) + 87.6\ (\%\ Ti)$$

Multiple correlation coefficient = 0.975

Standard error of estimate = 7,280 psi

Fracture-toughness data from the notched bend tests also were correlated with composition, as follows:

$$G_{Ic}(\text{in-lb/in.}^2) = 611 + 17.5\ (\%\ Co) - 7.34\ (\%\ Mo) - 512.8\ (\%\ Ti)$$

Multiple correlation coefficient = 0.848

Standard error of estimate = 93 in-lb/in.^{2}

The results of the above program led the company to specify the following composition for the 18Ni maraging steel for large-motor-case applications:

C	0.03 max	S	0.01 max	Co	7.5-8.5
Mn	0.10 max	Si	0.10 max	Mo	4.0-4.5
P	0.025 max	Ni	17.5-18.5	Ti	0.05-0.25

The alloy is to be produced by the consumable-electrode vacuum-arc remelting process.

In order to evaluate the material in sections thicker than 1/2-inch plate, one 10-ton heat was made into 3/4-inch plate and 1- and 4-inch-thick ring forgings. For the plate, the finishing temperature was below 1400 F and the cross-rolling reduction was 15 to 20 per cent. Typical properties obtained on transverse plate specimens aged at 900 F for 8 hours were 200-ksi yield strength, 208-ksi tensile strength, 10 per cent elongation, with a G_{Ic} value of 325 in-lb/in.^{2} from notched-bend tests.

Both TIG and MIG welding processes were used in preparing all-weld-metal specimens for tensile tests and welded joints for fracture-toughness tests. The data obtained indicated that TIG welding resulted in better ductility and toughness than MIG welding and that the strength was comparable to that of the plate. Consequently, TIG welding was selected as the preferred method. Tests to simulate repair welding by the TIG process also were made and indicated that repair welding had little effect on the properties.

The effect of test temperature on the tensile properties also was studied. Strength decreased gradually as the testing temperature was increased to about 700 F, above which temperature the decrease in strength was quite rapid.

Plate of 200-grade maraging steel was fabricated into a 36-inch-diameter pressure vessel and burst tested. In making this vessel, 10 to 12 passes were used per weldment, and one location required repair welding nine times. Failure occurred at a wall stress of 238 ksi which represented an 11 per cent biaxial gain. Failure initiated at the center of the longitudinal weld and there was a 10 per cent reduction in thickness at this point. The area of failure initiation did not involve a repair weld. Even though failure started at the weld, the results indicated the feasibility of fabricating large vessels of maraging steel by the roll-and-weld technique.

<u>Helically Welded 18 Per Cent</u>
<u>Nickel Maraging-Steel Vessels</u>
by Walter Hauck,
The Budd Company

This program involves development of a technique for fabricating pressure vessels by helical wrapping and butt welding 18Ni(250) maraging-steel strip that has been cold reduced 20 per cent. The strip was aged at 990 F before welding. An automatic TIG process was used in welding these vessels. The helical weld was oriented at an 11-degree angle to the axis of the vessel. After welding, the vessels were aged at 770 F. Strength of the welds was reported to be 70 to 80 per cent of the base-metal strength.

Results of recent pressure-vessel tests are as follows:

Vessel Diameter, inches	Strip Thickness, inch	Test Temp, F	Tensile Strength, ksi	Burst Stress, ksi	Gain, per cent
6	0.020	RT	255	284	11.4
20	0.040	RT	269	293	9.0
20	0.040	-65	297	326	9.8

Burst-test fractures in the vessels were longitudinal in direction and were 100 per cent shear. The fracture tended to avoid the welds.

Production of 80 small vessels is planned. The purpose is to evaluate the effect of test temperature, rate of pressurization, and production variables on strength and toughness.

Fracture-Toughness Characteristics of Maraging Steels
by P. P. Puzak,
U. S. Naval Research Laboratory

In this presentation, it was pointed out that when selecting materials for structures such as submarine hulls which may be 35 feet in diameter, 300 feet long, and constructed of plate 1 to 4 inches thick, one cannot rely on property evaluations made on comparatively thin specimens. Special testing methods for full-thickness plate of maraging steel and other high-strength steels were described. These included drop-weight tear tests and explosion tear tests on large plate specimens, and low-cycle fatigue tests on full-size pressure vessels. Standard Charpy tests are usually made in conjunction with these other tests.

Several variations of maraging steels are being evaluated including 18Ni, 12Ni, and 10Ni types. Air-melted material and vacuum-arc-remelted material are represented in the program. In addition, variations in heat treatment are being studied. The range of strength levels for the maraging steels in this program is 150 to 295-ksi yield strength.

Fracture toughness was pointed out as an important consideration in fabricated structures because it is impossible to detect all of the defects and flaws in the structure. If, at the prevailing service stresses and temperatures, the steel has sufficient flaw tolerance or fracture toughness to tolerate any small flaws that may be present, there should be no problem with brittle fracturing. However, small cracks and flaws may initiate fatigue cracks which may grow to considerable size under service conditions.

In discussing low-cycle fatigue cracks, one instance was mentioned in which a crack 16-1/2 inches long was formed in a 16-1/2-inch-thick plate. It apparently had started from small cracks at the location of an arc strike. Because of the problem of crack development under conditions of repeated stress, fatigue studies are being made on full-size pressure vessels of some of the steels.

Because of the extensive range of maraging-steel compositions and heat treatments under study, a wide range of values is being obtained for the various toughness parameters which are being used. For example, the drop-weight tear-test energies for these steels at 30 F vary from 7250 ft-lb for 157 ksi yield-strength material to less than 500 ft-lb for 250-ksi yield-strength material.

Application of the fracture-analysis diagram to the fracturing characteristics of these steels was discussed along with NDT values and methods for measuring NDT. The drop-weight tear test specimen is 3 inches wide with an additional brittle layer welded along one side. The brittle layer is notched. On impact, a brittle crack propagates through the brittle material and into the test material. The data obtained represent the energy absorbed as the crack passes through the specimen. In some respects the specimen is similar to a large Charpy specimen, but it is usually of full-plate thickness.

The explosion-tear-test specimen is 22 by 25 inches in size with a 2-inch crack in the midsection. A slot near each of the 22-inch edges permits restrained bulging of the midsection during explosion testing. Extent of crack development and per cent strain resulting from explosive testing are measured in evaluating the material.

For submarine-hull material, the fracture toughness as measured by the above tests on full-thickness specimens must be exceptionally high. In a summary plot of drop-weight tear energy versus yield strength for conventional quenched-and-tempered steels and maraging steels, it appeared that the maraging steels were comparable to some of the better quenched-and-tempered steels in the 150,000 to 190,000 psi yield-strength range. This program is being continued.

Session IV. Fabrication and Characteristics of Maraging Steel

Some Technical Aspects in the Manufacturing and Welding of Maraging Steel Plate
by H. Burns, Thiokol Chemical Corporation,
and F. Duffey, Newport News Shipbuilding and Drydock Company

Burns discussed the problems associated with production of heavy plate and thick sections of maraging steel. In the production of steel for 260-inch-diameter boosters, where components 2 to 4 inches thick may be required, massive ingots are used. Such ingots have a considerable tendency toward segregation. Consequently, a large amount of hot working and homogenization are necessary to produce plate with minimum effects from the segregation in the ingot.

As an example, for a straightaway-rolled ingot, 36 by 36 by 84 inches, the strength of annealed-and-aged specimens oriented in the short transverse direction of the rolled product was reported as 155 ksi with no ductility. The material was heavily banded. To avoid this condition, later ingots were forged during initial reduction and cross rolled during the rolling operations. With these modifications, the properties in the short transverse direction were 241-ksi yield strength, 251-ksi tensile strength, 2.6 per cent elongation, and 7.4 per cent reduction in area, with W/A of 425 in-lb/in.^{2} for precracked Charpy specimens. The material was 4 inches thick.

In discussing medium-thickness plate of 0.480-inch thickness, it was pointed out that cold straightening after mill annealing could be responsible for nonuniform properties in the plate product. The following precracked Charpy data were used to illustrate this effect:

Treatment	W/A, in-lb/in.^{2}
Mill annealed at 1600 F, cold straightened, aged at 900 F	750(L), 450(T)
Mill annealed at 1600 F, cold straightened, reannealed at 1600 F, aged at 900 F	948(L), 835(T)

These data show that some effect of directionality remained after the latter treatment. A 1650 F anneal appeared to be even more beneficial in breaking up the banded structure. The following data were supplied to illustrate the effect of the 1650 F anneal:

Treatment	W/A, in-lb/in.^{2}
As rolled, roller leveled, and aged at 900 F	595(L), 481(T)
Mill annealed at 1600 F and aged at 900 F	748(L), 543(T)
Mill annealed at 1600 F, reannealed at 1650 F for 1 hour, and aged at 900 F	899(L), 797(T)

Reannealing again at 1500 F followed by aging at 900 F resulted in no further improvement.

When two additional heats of plate were annealed at 1450, 1500, 1550, 1600, and 1650 F, it was found that the optimum reannealing temperature was 1550 F for one heat and 1500 F for the other. Tests were made in the longitudinal and in the transverse directions, and the criteria were W/A and G_n. This reconfirms conclusions reached by others to the effect that different heats respond differently to annealing and aging. Therefore, one must establish optimum reannealing and aging cycles for each heat in order to be assured that the expected properties are obtained.

Duffey discussed welding processes and welding problems associated with the production of large boosters by the roll-and-weld technique. For economical welding of large structures of thick plate, high rates of deposition are required along with soundness and good mechanical properties. Since Newport News had had experience with submerged-arc welding and since this process appeared to be most feasible from the standpoint of fulfilling the above requirements, it was the process that was selected for the development program for welding maraging-steel plate. Much development work was required to adapt this process to maraging steel. Of primary concern were the development of a suitable filler wire and a neutral flux.

Maraging-steel plates that were welded on this program were all air-melted 250 grade and were 1/2, 3/4, 1-1/4, 2, and 4 inches thick. Among the various tests that were used to evaluate the welded plates were fracture-toughness tests of the shallow-fatigue-crack type with the fatigue crack in the weld metal. The specimens were 8 inches long, 3/8 inch thick, and the same width as the plate thickness. The shallow fatigue crack was located at the root of the weld which was at the midsection of the specimen. For comparison, tests which were made on shallow-cracked specimens without welds indicated that the critical crack lengths were 0.2 to 0.3 inch depending on aging time at 900 F (for one heat of material). The corresponding notched strengths were 275 and 260 ksi.

Yield strengths of the welded specimens were 230 to 257 ksi. The welds contained 0.46 to 0.78 per cent titanium. With 1.20 per cent titanium in the welding wire, the titanium content of the weld metal was about 0.55 per cent. Union Melt 105 flux was used. The two-pass submerged-arc welding procedure developed on this program yielded substantially better properties than that for multipass welds. The two-pass procedure could be used for plate to 1-1/4 inches thick. Thicker plate required more than two passes.

Critical crack lengths for welded specimens were usually in the range 0.07 to 0.13 inch with corresponding notch strengths from 260 to 230 ksi. For one series of specimens containing high-quality welds, the average critical crack length was 0.1 inch at an average strength of 246 ksi.

Tensile specimens from welded plate always failed in the heat-affected zone. Fracture occurred in the "eyebrow" area of the heat-affected zone where reversion to austenite had taken place.

Thermal-shock delamination of maraging-steel plate has been observed following plasma-arc cutting and high-heat submerged-arc welding. This has been detected by dye-penetrant indications. However, it was reported that thermal-shock delamination now can be avoided by the use of new material and new cutting techniques.

A more serious problem was restraint-solidification weld cracking in thick plate (2 inches and more). This cracking occurs along the center of the weld bead under highly restrained conditions. The problem was overcome by having the joint in a vertical position (vertical submerged-arc welding). By this method, sound welds were obtained with no cracks. Even though the heat-affected zone was relatively large, it responded completely to aging except for a narrow band. The response could be further improved by reannealing before aging. For vertical submerged-arc weldments made in 250-grade maraging steel, yield strengths of about 240 ksi were reported. The critical crack length of the weld metal was about 0.16 inch.

Particles of reverted austenite were found between the dendrites in the weld-metal structure. The weld deposit was relatively large grained. Submerged-arc deposits were observed to be sensitive to hydrogen embrittlement; 4 ppm of hydrogen was the limit. For highly restrained joints, it was thought that even less hydrogen could be tolerated. Very few inclusions occurred in the weld deposit.

<u>Status of Manufacturing-Process Development for High-Strength Steels</u>
by T. Shimmin,
Republic Steel Corporation

This program involves a comprehensive study of the processing variables associated with the production of 18Ni(250) and 18Ni(300) maraging steels and 9Ni-4Co(200) and (250) alloy steels. The products include sheet, plate, forgings, and forged rings. Studies of melting, forging, and rolling practices will be made and the relationship of the processing variables to the properties of the end products will be evaluated. Eleven air-melted, 10 vacuum-arc remelted, and one electroslag-remelted heats have been produced. The air-melted heats were 5 to 85 tons, the vacuum-arc remelted heats were 2 to 13 tons, and the electroslag heat was 4 tons. Both Si-Al deoxidation and vacuum-arc remelting with carbon deoxidation are being studied for the 9Ni-4Co heats. Ingots from these heats have been forged to intermediate-size billets, and tests are being made to determine the preferred finished-product forging and rolling practices.

The three phases of this program are: (1) literature survey, (2) process development, and (3) product evaluation. The final criterion of the success achieved in determining the optimum processing procedures will be the reproducibility that can be obtained in the strength and toughness properties of the alloys when processed according to the optimum procedures.

In addition to variations in melting practice, the following variables are being studied in regard to forging practice: (1) ingot-breakdown temperature, (2) product-finishing temperature, and (3) forging reduction.

Variations being studied in connection with rolling procedures are: (1) starting temperature, (2) finishing temperature, and (3) cross-rolling ratio. Final studies will include variations in heat treatment, welding procedures, and production-risk factors since these are all related to product producibility and the economics of production. Results of qualification tests on six heats were noted.

A new objective, evaluation of these steels for 260-inch-diameter Y-rings for solid-propellant motor cases, has been added to the program. Two 43-inch octagonal 20,000-pound ingots of air-melted 18Ni(250) maraging steel were cast for this part of the program along with one 32-inch-diameter 28,000-pound vacuum-arc remelted ingot and some smaller ingots. During processing of the two 43-inch-octagonal ingots to 30-inch-square billets, each developed a deep longitudinal crack which made salvage impossible.

During this same period, the large vacuum-arc remelted ingot, the smaller VAR ingots, and the air-melted ingots were forged to the intended billet sizes without any problems from crack development.

An investigation is being conducted to determine the cause of cracking in the billets from the large air-melted ingots. Effects of hydrogen embrittlement, microstructure, and other variables are being studied, while specimens from the ingots that did not crack are being evaluated for comparison purposes.

Strengthening Mechanism of 18 Per Cent Nickel Maraging Steels
by B. G. Reisdorf and A. J. Baker
(presented by G. E. Pellissier),
U. S. Steel Corporation

The purpose of this program is to determine the mechanisms that cause strengthening when commercial heats of 18Ni(250) and 18Ni(300) maraging steels are aged. Five heats had been studied up to the time of this project-review meeting. Steel A was an air-melted 20-ton heat of 18Ni(250) grade. Steel B was a 15-ton consumable-electrode vacuum-arc remelted heat of 18Ni(300) grade. Steels C, D, and E were 300-pound vacuum-melted vacuum-carbon-deoxidized heats containing 18 per cent nickel and 7 per cent cobalt. In addition, Steel C contained 5 per cent molybdenum, Steel D contained 0.4 per cent titanium, and Steel E contained 0.4 per cent aluminum. Each heat was hot rolled to 7/8-inch plate from which the specimens for the program were prepared. Aging reponse based on hardness measurements was studied for each of the five heats for aging temperatures of 750, 800, 850, and 900 F for times of 100 hours and more, depending on the time required to develop maximum hardness. Tensile and Charpy impact properties were obtained on all heats after annealing at 1500 F and aging at 900 F for 3 hours. Plane-strain fracture toughness data were obtained on notched-and-fatigue-cracked round bars of Steels A and B. The properties of these two steels were typical of their particular grade.

After heating the five steels at 1500 F and cooling in air to room temperature, the transformation from austenite was at least 99.5 per cent complete in all five heats. A transmission electron micrograph of the martensite in Steel A showed a high dislocation density similar to carbon martensites, but few if any microtwins which are frequently observed in carbon martensites. An extraction replica showed a large number of roughly spherical particles identified as Ti(C,N).

After aging Steel A at 900 F for 3 hours, two types of particles were observed in both transmission electron micrographs and extraction replicas. These were roughly spherical particles about 100 angstroms in diameter and rod-shape particles. The distribution of the latter particles resembled the original dislocation distribution and suggested that they were dislocation nucleated. Identification of the particles was difficult for specimens aged 3 hours at 900 F. After aging for 8 hours at 900 F, the same two types of particles were observed but they were slightly coarser. Electron diffraction revealed Ni_3Mo, Ti(C,N), and austenite; Ni_3Ti also may have been present. The major precipitate consisted of the rod-shape particles of Ni_3Mo.

After aging for 30 hours at 900 F, an electron micrograph revealed massive particles of reverted austenite in the structure as well as the rod-shape and spherical-shape particles. Stereoscopic examination, however, indicated that the latter two species were probably ribbon shape and disk shape, suggesting growth in a planar fashion.

Examination of Steel A after aging for 80 hours at 900 F showed that most of the precipitate particles were disk shape and that many larger plates of reverted austenite were present. Austenite reversion was not limited to nucleation within the grains but also occurred at the martensite and prior austenite grain boundaries.

The microstructures of Steel B as annealed and as annealed and aged were nearly the same as for Steel A. However, in Steel B the titanium content of the precipitate particles was nearly twice that for Steel A (Steel B contained about twice as much titanium).

Steel C, which was the 18Ni-7Co-5Mo alloy, contained a large amount of massive particles of M_6C type which interfered with identification of the age-hardening precipitates. The M_6C particles were not present after austenitizing at 2100 F and water quenching. The structure was then similar to that for Steels A and B in the annealed condition.

After aging Steel C for 3 hours at 900 F, the precipitate particles were very thin and ribbon shape. No diffraction patterns could be obtained on these particles. After 8 hours at 900 F, Steel C achieved maximum hardness and the disk-shape particles appeared with the ribbon-shape particles.

Steel D contained 18 nickel, 7 cobalt, and 0.4 titanium. The annealed or martensitic structure was somewhat different from that of the other steels since the martensite had a more equiaxed appearance with fewer dislocations. After aging for 3 hours at 900 F, small spherical particles and thin rod-shape particles could be observed in the structure. Aging for 80 hours at 900 F produced reverted austenite along with the spherical and rod-shape particles. Electron-diffraction patterns indicated the presence of austenite and Ti(C,N).

The martensite formed in Steel E (18Ni-7Co-0.4Al) on cooling from 1500 F to room temperature was similar to that for Steels A and B. The age-hardening response at 900 F was slight, but aging at 750 F resulted in a more effective response. A dense dispersion of a fine precipitate was observed in specimens aged for considerable times at 750 and 800 F, but the identity of these particles was not yet known.

Session V - Alternate Motor-Case Materials

Development of Welding Procedures for Joining 9Ni-4Co-0.20C Steel

by J. M. Gerken,
Thompson Ramo Wooldrige, Inc.

The objective of the program described was to develop procedures and filler wire to weld the 9Ni-4Co-0.20C steel at the 180- to 200-ksi yield-strength level, with joint efficiencies of 95 per cent and more. This type of steel is hardened by quenching and tempering, and a further objective of the program was to develop satisfactory joint properties without preheat or postheat.

The test materials represented two heats of steel, one in the form of 1/2-inch plate and the other in the form of 0.090-inch sheet. The mechanical properties of these materials were evaluated as a function of tempering temperature from 400 to 1100 F. Tempering at 400 F, after austenitizing at 1550 F for 30 minutes, gave 200-ksi yield strength and 240-ksi ultimate tensile strength. These properties did not decrease much until a tempering temperature of about 1000 F was reached, and then they dropped rapidly. Fracture toughness, as indicated by K_{I_c} values obtained from precracked slow-bend tests, reached a maximum of 105 ksi $\sqrt{\text{in.}}$ on tempering at 950 F.

TIG and MIG welding methods were investigated using standard bead-in-groove specimens. No preheat nor postheat was used, and interpass temperature was maintained at room temperature. Longitudinal all-weld-metal tensile tests and transverse tensile tests which included weld, heat-affected zones, and base metal were made.

In the studies of TIG welding on 1/2-inch plate, speeds of 4, 10, 15, and 25 inches per minute were used. Good results were obtained when the speed was 10 inches per minute. Faster speeds introduced porosity; while at slower speeds, the yield strength tended to be too low. Sounder and stronger welds were obtained with helium than with argon at any given rate of travel. Weld-metal tensile strength was strongly influenced by carbon content. At 0.20 per cent carbon, the yield strength was 185 ksi; at 0.22 per cent carbon, it was 190 ksi; at 0.24 per cent carbon, the value was 195 ksi; and at 0.27 per cent carbon, the yield strength was 200 ksi. These values were all equal to, or better than, that of the base metal. Transverse tensile tests all failed in the base metal and, therefore, it could be said that the joint efficiency was 100 per cent. All the TIG-welded joints gave K_{I_c} values greater than the upper limit that could be determined accurately with the specimen configuration available (i.e., a 1/2-inch-square section).

TIG welding at the rate of 10 inches per minute on 0.090-inch sheet gave joint efficiencies of 95 to 100 per cent for yield-strength levels of 182 to 188 ksi. The corresponding ultimate strengths were 208 to 216 ksi and the elongations were 11 to 12 per cent. Both helium and argon were used.

MIG welding of the 1/2-inch plate was not as successful as TIG welding. On a yield-strength basis, joint efficiencies were less than 95 per cent.

Booster-Case-Materials Evaluation

by J. N. Masters,
The Boeing Company

The initial phase of a program begun in 1962 was an evaluation of several materials for possible application in large motor cases. The materials were 18Ni(300), 18Ni(250), 20Ni(250), HP-150, Ladish D6A and D6AC steels, and 6Al-4V titanium alloy. These alloys ranged in tensile strength from some 150 ksi to 300 ksi or more. Properties of base metal and TIG weldments were studied. The principal criteria were economics and mechanical properties. The significant findings were that important increases in critical-flaw sizes could be realized by using materials of moderate strength rather than ultrahigh strength, and that the economics were not affected to any great degree by the strength of the material. Thus, there appeared to be good reason to consider seriously materials of moderate strength, say, 150- to 200-ksi tensile strength. More research on the load-carrying behavior of such alloys was clearly indicated.

As the program continued, a study was made of the critical-flaw sizes in the various parts of a case at expected operating stresses, the maximum initial flaw size likely to exist, and the manner in which the initial flaw might grow to critical size and cause premature failure. Critical-flaw size was determined from K_{I_c} measurements and the applied stresses.

Maximum initial flaw size was dependent on nondestructive-inspection capabilities and could also be arrived at through the proof testing procedure. This flaw size can be calculated from the stress vs K_{Ic} vs flaw-size equation by inserting the K_{Ic} value for the material and the proof stress used, and then solving for the flaw size. Furthermore, these interrelationshps permit choosing, with considerable accuracy, a proof stress commensurate with the expected service conditions and life. What should be known, to complete the scheme, is the way in which the defect may grow to critical size. With this knowledge, a proof stress can be selected so as to "inspect" the structure for the presence of defects too large to be tolerated during the expected service life, even though they are initially subcritical at the design operating stress.

Sustained-load tests at Boeing have indicated that slow crack growth is usually not significant unless the critical intensity is quite large with respect to the critical. The exceptions would appear to be instances involving such phenomena as corrosion or hydrogen embrittlement.

In another phase of the program, fracture-toughness and tensile data were obtained on a number of possible booster-case materials. The alloys were studied in the form of 3/4- or 1-inch plate and TIG butt weldments made in the plate. The materials studied were 18Ni(200) vacuum melted, 18Ni(200) air melted, 12Ni(180) air melted, HY-150 air melted, HP-150 vacuum degassed, and 9Ni-4Co-0.25C vacuum degassed. Yield strengths ranged from 140 to 219 ksi. Base-metal K_{Ic} values were generally 130 ksi $\sqrt{in.}$ and higher. The toughness of weldments was usually at least 80 per cent that of the base metal. For the 12Ni(180) steel, the K_{Ic} of the weldment was considerably less.

<u>Properties of HP 9-4-X Alloy Steels</u>
by J. S. Pascover and S. J. Matas,
Republic Steel Corporation

This presentation was a report on certain aspects of the development of the 9 per cent nickel, 4 per cent cobalt steels. The data given were based on tests of some 30 production-sized heats and several hundred laboratory melts. Emphasis was placed on strength and toughness characteristics.

Vacuum carbon deoxidation was observed to result in the cleanest steel with the lowest gas content. Steel produced by this practice had greater toughness, as indicated by notch tensile strength, than had aluminum-silicon deoxidized metal. However, in many cases, this practice might not be necessary for the tougher lower carbon members of the 9Ni-4Co family.

As to composition, it was recognized that carbon should be kept as low as is commensurate with strength requirements, in the interests of toughness and weldability. Nickel was used to promote toughness and hardenability, while cobalt was added to counteract the tendency of nickel toward austenite retention as well as to promote self-tempering in as-quenched or as-welded structures by raising the M_s temperature. In the higher carbon steels, i.e., about 0.40 per cent carbon or so, carbide-forming elements were considered detrimental to toughness. Chromium decreased the yield-to-tensile strength ratio and reduced the tendency toward plastic instability.

These steels retained considerable strength even after tempering at quite high temperatures. For example, the 9-4-25 type retained a yield strength of about 190 ksi, with a Charpy V-notch value of 50 ft-lb, on tempering at 1000 F. At any given yield-strength level, the bainitic structure was tougher than tempered martensite, except at the very highest strengths.

K_{Ic} values ranging from 100 to 150 ksi $\sqrt{in.}$ were reported for 9-4-25 steel plate, depending on the strength level and the heat-treating procedure. K_{Ic} values reported for weldments having 95 per cent or more joint efficiency were 120 to 135 ksi $\sqrt{in.}$, for the as-welded condition. The endurance limit for unnotched fatigue specimens was about 50 per cent of the tensile strength. When loaded to 80 per cent of the yield strength, specimens of this steel showed no failure after 1000 hours in 3.5 per cent NaCl solution.

For good weldability and hardenability in very thick sections, say to 6 inches, the carbon was lowered to 0.18/0.24 per cent and the chromium and molybdenum were increased to 1 per cent each.

The higher carbon, higher strength 9-4-45 alloy was reported to show K_c values in the order of 150 ksi $\sqrt{in.}$ at yield strengths of 240 to 260 ksi, when in the form of sheet up to 1/4 inch thick. The K_{Ic} values for heavy sections were in the range of 60 ksi $\sqrt{in.}$ for a tempered martensitic structure and 80/90 ksi $\sqrt{in.}$ for a bainitic structure at the same strength.

From the data presented, it appeared that, at yield strengths above about 230 ksi, the 18Ni maraging steels had superior plane-strain fracture toughness. At about 210- to 230-ksi yield strength, K_{Ic} values for bainitic 9-4-45 steel and 18Ni maraging steel were comparable. At yield strengths of 180 to 210 ksi, the 9-4-25 steel was clearly the tougher material.

<u>Welding of 9Ni-4Co Alloy Steels</u>
by G. D. Ries and S. W. Poole,
Republic Steel Corporation

Some studies which have been made on the welding of the 9Ni-4Co type of steel were reported. An investigation of the behavior of the 0.20 and 0.25 per cent carbon varieties, in the form of 1/2- and 1-inch plate, showed great resistance to cracking when butt welded by the TIG process under conditions of severe restraint. In guided side-bend tests, 3/8 by 1 inch, TIG butt welds in the 9-4-20(Cr,Mo) steel were able to negotiate a 2T bend without cracking or tearing.

TIG weldments in 1/2-inch 9-4-25 steel plate were reported to show a full 100 per cent joint efficiency and room-temperature Charpy V-notch values of 25 ft-lb for the as-welded condition. Yield strengths were in the order of 198 ksi. In 1-inch plate, joint efficiences were 90 per cent and more with Charpy V-notch values of 37 to 46 ft-lb at room temperature and 31 to 37 ft-lb at -80 F. Corresponding base-metal Charpy values were 46 to 53 ft-lb and 42 to 46 ft-lb, respectively. The composition of the filler wire was similar to that of the base metal.

TIG welding of the lower carbon version of the 9Ni-4Co alloy, containing increased amounts of Cr and Mo, was also investigated. In 1/2-inch plate, joint efficiencies of 93 per cent and over were reported with Charpy V-notch values quite comparable to those of the base plate.

It was found that the higher carbon grade of 9Ni-4Co steel should be welded in the as-annealed condition for best results. The structure is then hardened and tempered after welding. In welding the lower carbon steels, neither preheat nor postheat is required.

Welding the 9Ni-4Co steels with the MIG process, using direct current, seems to be impractical at the moment. However, with special techniques, MIG welding with alternating current seems possible.

<u>HP-150: An Alloy With High Strength and Maximum Toughness</u>
by H. P. Munger,
Republic Steel Corporation

Properties for a low-alloy quenched-and-tempered steel, developed by Republic Steel Corporation and designated as HP-150, were reported. The nominal composition of this steel is 0.25 carbon, 3.0 nickel, 1.50 chromium, 0.90 molybdenum, 0.05 columbium and balance iron. This steel was designed to combine toughness with high strength (about 155-ksi yield strength) and good weldability with no postheat required. However, local preheat to about 300 F is recommended.

Mechanical properties were reported for the steel in the form of 1-inch plate as melted and deoxidized according to different practices. One method involved induction stirring and ladle degassing of electric-furnace-melted metal using carbon deoxidation. Another practice combined consumable-electrode vacuum-arc remelting with carbon deoxidation. Still another practice was to combine consumable-electrode vacuum-arc remelting with induction stirring and ladle degassing. The purpose of these practices was to reduce the nonmetallic inclusion and gas contents of the steel.

A K_{Ic} value of 155 ksi $\sqrt{\text{in.}}$ was reported for vacuum-arc-remelted and carbon-deoxidized metal in the longitudinal direction at a yield strength of 157 ksi. A drop-weight NDT temperature of -150 F was given for a longitudinal specimen of the same steel at 158-ksi yield strength. For the same strength level, Charpy V-notch values at -80 F of 57 ft-lb for the transverse direction and 58 ft-lb for the longitudinal direction were obtained.

It was reported that when the alloy can be TIG welded, or can be heat treated after welding, it is not difficult to obtain 100 per cent joint efficiency. It was also stated that MIG welding procedures have been developed giving joint efficiencies of more than 97 per cent of the base-metal yield strength. Satisfactory MIG welds were reported for plate both 1 and 2 inches thick.

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Number	Title
1	Thermal Properties of Titanium and Titanium Alloys, August 25, 1958 (PB 161152, $0.50)
2	Some Notes on Safe Handling Practices for Beryllium, September 22, 1958 (PB 161153, $0.50)
3	Recent Advances in Titanium Technology, October 24, 1958 (PB 161154, $0.50)
*4	Effects of High Strain Rates and Rapid Heating on the Tensile Properties of Titanium Alloys, December 29, 1958 (PB 161155, $0.50)
*5	The Influence of Sheet Thickness on Tensile Properties of Metal Sheet, January 23, 1959 (PB 161156, $0.50)
6	The Status of Chromium-Base Alloy Development, January 30, 1959 (PB 161157, $0.50)
7	Implications of Rhenium Research in the Design of Refractory Metals, February 2, 1959 (PB 161158, $0.50)
8	Elevated-Temperature Mechanical Properties and Oxidation Resistance of Columbium and Its Alloys, February 4, 1959 (PB 161159, $0.50)
9	Preparation and Analysis of Titanium-Hydrogen Standard Samples, February 9, 1959 (PB 161160, $0.50)
10	Commercial and Semicommercial Titanium Mill Products, February, 1959
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*13	Joining of Beryllium, March 30, 1959 (PB 161163, $0.50)
*14	Physical and Mechanical Properties of Molybdenum and the Mo-0.5Ti Alloy, April 10, 1959 (PB 161164, $0.50)
15	Mechanical- and Physical-Property Data on Modified 12 Per Cent Chromium Martensitic Stainless Sheet Steels for Airframe Applications, April 18, 1959 (PB 161165, $0.50)
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17	Future Application Trends for Titanium and Steel in Military Aircraft, May 8, 1959 (PB 161167, $0.50)
18	Fabrication of 17-7PH and PH15-7Mo Stainless Steel by Bend Rolling, Deep Drawing, and Spinning, May 15, 1959 (PB 161168, $0.50)
19	The Availability and Properties of Rhenium, May 22, 1959 (PB 161169, $0.50)
20	The Properties of Magnesium-Thorium Alloys, May 29, 1959 (PB 161170, $0.50)
21	Machining of Beryllium, June 5, 1959 (PB 161171, $0.50)
*22	Routing of Titanium Sheet, June 12, 1959 (PB 161172, $0.50)
23	Band Sawing of Titanium and Titanium Alloys, July 1, 1959 (PB 161173, $0.50)
24	Hacksawing of Titanium and Titanium Alloys, July 6, 1959 (PB 161174, $0.50)
25	Profile Milling Titanium and Its Alloys, July 10, 1959 (PB 161175, $0.50)
26	Spindle Shaping of Titanium Sheet, July 15, 1959 (PB 161176, $0.50)
*27	Arc Welding of High-Strength Steels for Aircraft and Missile Structures, July 31, 1959 (PB 161177, $0.50)
28	Review of Electrical Machining Methods, August 5, 1959 (PB 161178, $0.50)
*29	Nitriding of Titanium, August 12, 1959 (PB 161179, $0.50)
30	Milling of High-Strength Steels in the Hardness Range of 330 to 560 Brinell, August 17, 1959 (PB 161180, $0.50)
31	Drilling High-Strength Steels Heat Treated to 330 to 560 Brinell Harnness, August 24, 1959 (PB 161181, $0.50)
32	Physical and Mechanical Properties of Tantalum, August 28, 1959 (PB 161182, $0.50)
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*39	Development of High-Strength Steels by Working of Metastable Austenite, November 30, 1959 (PB 161189, $0.50)
40	A Brief Review of Refractory Metals, December 3, 1959 (PB 161190, $0.50)
41	The Properties of Boron, January 4, 1960 (PB 161191, $0.50)
42R	Standard Designations of Alloys for Aircraft and Missiles, May 24, 1961 (AD 233728, $0.50) Obsolete, Memo 177
43	Notes on Mechanical Testing Techniques at Very Low Temperatures, February 19, 1960 (PB 161193, $0.50)
44	Refractory Materials, February 26, 1960 (PB 161194, $0.50)
45	Recent Developments in Titanium Brazing, March 4, 1960 (PB 161195, $0.50)
46	Fatigue Data on Precipitation-Hardenable Stainless Steel, March 11, 1960 (PB 161196, $0.50)
47	Selected References on Making High-Temperature Alloys by Powder Metallurgy, March 18, 1960 (PB 161197, $0.50)
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13. ABSTRACT

This memorandum summarizes the Fourth Maraging-Steel Project Review which was held on June 9 to 11, 1964, in Dayton, Ohio. During the sessions, twenty-one scheduled and several unscheduled presentations were made by representatives of Government agencies, industrial concerns, and universities. Abstracts of these presentations are included in this memorandum preceded by a summary of the highlights of the various technical developments. Session I dealt with the mechanical properties of maraging steels. The remaining four sessions dealt with general maraging-steel evaluations, mechanical properties of welds and fabrication of 18 per cent nickel maraging steels, fabrication and characteristics of maraging steels, and alternate motor-case materials. During the past year, considerable effort has been expended to resolve certain technical problems relating primarily to 18 per cent nickel maraging-steel plate which has been under consideration for large booster cases. Among these problems have been banding and the resultant low short-transverse mechanical properties, low fracture toughness of welds, and variations in mechanical properties, associated with mill processing variables. The results of the research programs presented at this meeting shed much light on these and other problems and indicate that considerable progress has been made toward overcoming the production and fabrication problems of the maraging steels and other high-strength steels.

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Cold working						
Fracture toughness						
Pressure vessel						
Mechanical properties						
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