Mechanical Behavior of 18 Ni 200 Grade Maraging Steel at Cryogenic Temperatures

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A comprehensive study was conducted to characterize the mechanical behavior of 18 Ni 200 grade maraging steel for cryogenic applications in the National Transonic Facility. Tensile, fatigue, impact, and fracture toughness properties were determined at room and cryogenic temperatures. The experimental variables included the product form, specimen orientation, and variations in the metallurgical condition accomplished with a grain-refining heat treatment. The room temperature tensile yield strength was ~200 ksi and the yield strength at −275°F ~260 ksi. Charpy V-notch energy absorption values and fracture toughness values of the 18 Ni steel were found to be dependent on temperature, product form, orientation, and metallurgical condition. Fracture toughness values were 80-113 ksi-in.$^{1/2}$ at room temperature and 66-90 ksi-in.$^{1/2}$ at −275°F. The results of this study indicate that 18 Ni 200 grade maraging steel exceeds the strength criterion of a 150 ksi minimum yield strength for use in cryogenic wind tunnel models, but is marginal with respect to the 85 ksi-in.$^{1/2}$ fracture toughness criterion at −275°F.

Nomenclature

A	= bar axial direction
a	= crack length
B	= thickness
COD	= crack opening displacement
da/dN	= fatigue crack growth rate
K	= stress intensity factor
K_{Ic}	= plane-strain fracture toughness
K_Q	= conditional fracture toughness value prior to K_{Ic} validity check
ΔK	= stress intensity range
L	= plate longitudinal direction
P_{min}	= minimum load
P_{max}	= maximum load
P_Q	= conditional load value used for K_Q calculation
ΔP	= load range
R	= bar radial direction
S	= plate short transverse direction
Sp	= span
SENB	= single-edge-notch bend specimen
T	= plate transverse direction
W	= width
α	= ferrite
γ	= austenite

Introduction

THE National Transonic Facility (NTF) at the NASA Langley Research Center was designed to exploit the research opportunities made possible by operating a wind tunnel at cryogenic temperatures and high dynamic pressures. The advantage of cooling the test gas to cryogenic temperatures is the resulting ability to achieve the values of Reynolds numbers comparable to those of commercial aircraft. Operating a tunnel at extremely low temperatures will result in much better aerodynamics simulations, but will also result in more demanding structural requirements for the metallic materials used in model fabrication. Although the strength of most materials is increased at low temperatures, a significant decrease in fracture toughness is often observed. This decrease in fracture toughness has created a new challenge in the selection of materials for balances, stings, and models that require a material to exhibit high strength and high toughness at cryogenic temperatures. Relatively few materials have been identified as candidates for cryogenic wind tunnel models and support hardware as a result of the stringent combined design criteria of 150 ksi yield strength and 85 ksi-in.$^{1/2}$ fracture toughness at −275°F. These criteria were established as a Langley policy in the publication "Wind-Tunnel Model Systems Criteria," which also sets forth other mandatory requirements for models to be tested in the NTF.[1] One material currently being used in the fabrication of NTF model systems is 18 Ni 200 grade maraging steel with cobalt as its primary strengthening agent. This alloy was identified as having potential for application at cryogenic temperatures, but the reported property data[2] were limited to metallurgical conditions not necessarily optimized for cryogenic use. To insure that the structural integrity of model systems fabricated from this material is maintained, a comprehensive study was conducted to characterize the mechanical behavior at cryogenic temperatures. In the program, tensile, impact, fatigue, and fracture toughness properties were determined at room and cryogenic temperatures. The primary objective of this investigation was to characterize the mechanical behavior of 18 Ni 200 grade maraging steel as affected by a set of experimental test variables to determine its suitability for cryogenic applications.

Experimental Procedure

Material

The material used throughout this study was 18 Ni 200 grade maraging steel (registered tradename VascoMax 200 by manufacturer, Teledyne Vasco). The nominal and x-ray spectrochemical measured composition and typical microstructure of fully aged 18 Ni steel are shown in Table 1 and Fig. 1. The microstructure of this alloy consists of nickel martensite with precipitates rich in nickel and molybdenum. The strength of this alloy is derived through the maraging process, which is a combination of a shear transformation and a precipitation-hardening reaction. The material was obtained in the annealed condition and was given either the

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standard aging heat treatment of 900°F for 3 h or a grain-refining heat treatment and subsequent standard age heat treatment. Regardless of the heat treatment, the final hardness of the maraging steel was R_c 43-45.

Grain Refinement

Several investigators have demonstrated the beneficial effects of grain refining on cryogenic impact behavior and fracture toughness.[3,4] The present study employed a grain-refining heat treatment schedule which was previously developed at Langley Research Center (LaRC) in an effort to improve the cryogenic strength and toughness of martensitic alloys.[3] The heat treatment involves multiple thermal cycles between the single-phase (γ) region and dual-phase (γ and α) region to reduce the grain size, followed by an annealing step and a standard age of 900°F for 3 h (Fig. 2). By holding the maraging steel in the single-phase region, there is a decrease in grain size to release internal strain accumulated during the prior diffusionless shear transformation. The grain size is also reduced by holding the material in the dual-phase region where it is postulated that refinement occurs by preferential nucleation of γ on the boundaries of martensite plates.[4] This heat treatment was successful in reducing the grain size from 40-50 μm to 5-10 μm (compare Fig. 1 with Fig. 3).

Experimental Variables

The experimental variables evaluated in this program included test temperature, product form, specimen orientation, and metallurgical condition. Tests were conducted at room temperature, −150°F, and −275°F. The effect of product form on mechanical properties was evaluated by machining specimens from 4.5 in. thick plate and bar stock having diameters 1-8 in. Specimen orientations were determined so that directions of principle loading were examined. In the plate material, specimens were oriented in both longitudinal and transverse directions (Fig. 4). In the bar stock, radial and axial planes and directions were investigated (Fig. 5). The maraging steel was tested in both the standard aged condition and a grain-refined/aged condition.

Table 1 Nominal and measured composition of 18 Ni 200 grade maraging steel

Element	Nominal, %	Measured, %
Nickel	18.50	18.80
Cobalt	8.50	8.65
Molybdenum	3.25	2.97
Titanium	0.20	0.22
Aluminum	0.10	—

Mechanical Testing

The mechanical behavior of 18 Ni 200 grade maraging steel was evaluated using tensile, Charpy, and fracture toughness tests. Prior to mechanical testing, the low-temperature elastic modulus of the maraging steel was statically determined on actual tensile test specimens using the method described in ASTM E 231.[5] Modified 0.505 in. diam tensile specimens were tested in a 100,000 lb capacity closed-loop hydraulic test frame to determine yield strength and ultimate tensile strength at room temperature and −275°F. The impact strength of the maraging steel was determined using standard 0.394 in. thick Charpy V-notch specimens. Energy absorption data were obtained at room temperature and −275°F using the method outlined in ASTM E 23.[6]

Fatigue crack growth rates and fracture toughness values were determined using 1×1×5 in. long single-edge-notch bend (SENB) specimens and the procedure in ASTM E 399.[7] Tests were conducted in a closed-loop electrohydraulic machine equipped with an environmental chamber and three-point bend test apparatus (Fig. 6). The test temperature was controlled within ±5°F. Fatigue precracking conducted at room and cryogenic temperatures was monitored using a clip-on crack opening displacement (COD) gage. By systematically sampling COD output with a data acquisition system and employing a previously developed compliance relationship for SENB specimens,[8] the effective crack length was determined during the fatigue precracking procedures. Crack growth rate, da/dN was then determined at various ΔK levels by differentiating the curve of effective crack length vs number of cycles. Fatigue stress intensity factors were determined from

$$\Delta K = \frac{\Delta P S p}{B W^{3/2}} \cdot f(a/W) \tag{1}$$

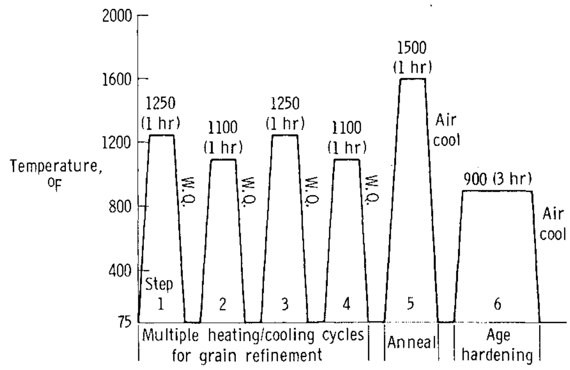

Fig. 2 Grain refining thermal treatment for 18 Ni 200 grade maraging steel.

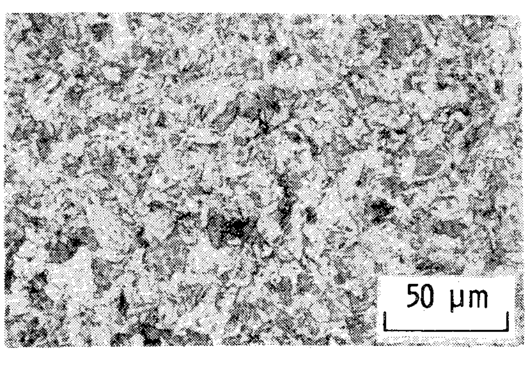

Fig. 1 Microstructure of standard aged 18 Ni 200 grade maraging steel.

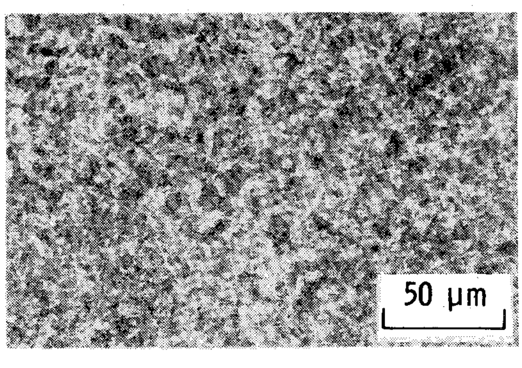

Fig. 3 Microstructure of grain refined/aged 18 Ni 200 grade maraging steel.

where

$$\{3(a/W)^{1/2}[1.99-(a/W)(1-a/W) \times [2.15-(3.93a/W)+(2.7a^2/W^2)]\} \div [2(1+2a/W)(1-a/W)^{3/2}] \quad (2)$$

The specimen loading was such that the load ratio, P_{min}/P_{max}, was equal to 0.1 and ΔK increased with increasing crack length.

After fatigue precracking procedures, the specimens were loaded to failure in the three-point bend apparatus at the desired test temperature. The fracture toughness of the maraging steel was determined using the load vs crack opening displacement curves obtained with an *x-y* plotter and data acquisition system. All fracture toughness tests were carried out at the same temperature at which the specimen had been fatigue precracked.

Results and Discussion

Low-Temperature Modulus

Young's modulus of elasticity of the maraging steel was statically determined at room and cryogenic temperatures according to ASTM E 231.[5] The experimental determination of the modulus at room temperature of 26.3×10^6 psi is in close agreement with the manufacturer's reported value of 26.2×10^6 psi.[9] The low-temperature modulus measurements were made at −100, −200, and −250°F. As shown in Fig. 7, there was a linear increase in modulus with decreasing temperature. The heat treatment had no effect on the elastic modulus of the maraging steel. The modulus values determined were used in the analytical calculations for determining the fatigue and fracture toughness behavior of the material.

Tensile Testing

A summary of the mechanical properties of 18 Ni 200 grade maraging steel is presented in Table 2. The tensile properties of 18 Ni 200 grade maraging steel in the various prod-

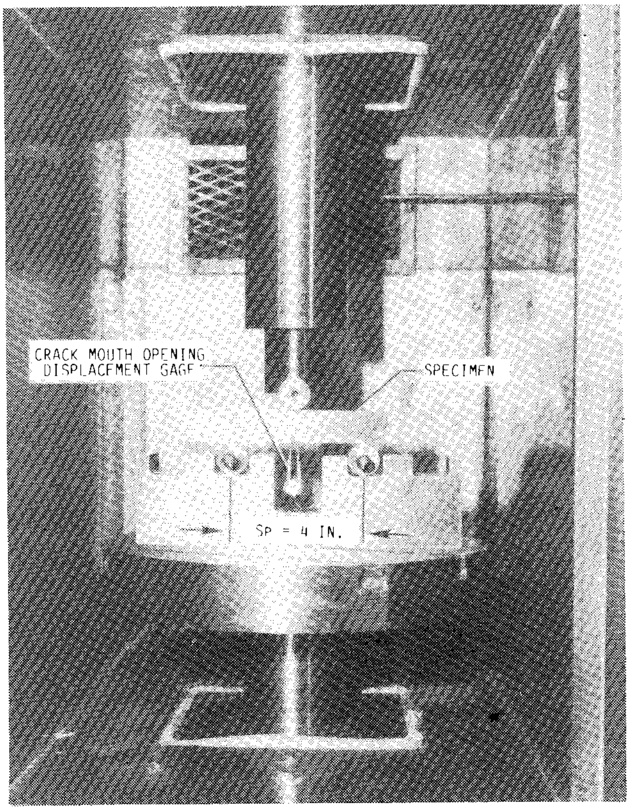

Fig. 6 Three-point bend apparatus in environmental chamber for fatigue crack growth and fracture toughness testing.

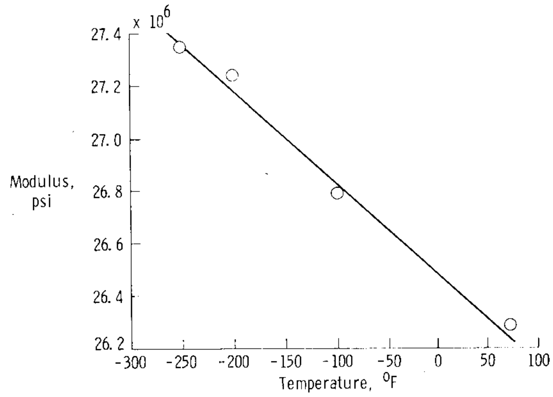

Fig. 7 Effect of temperature on elastic modulus for 18 Ni 200 grade maraging steel.

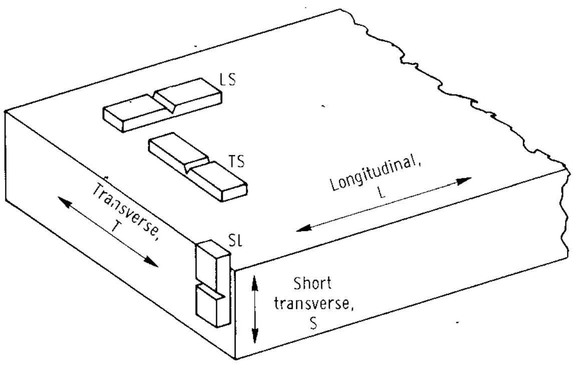

Fig. 4 Specimen orientation in plate stock material.

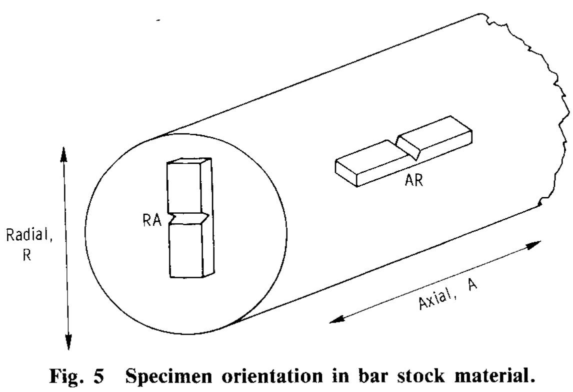

Fig. 5 Specimen orientation in bar stock material.

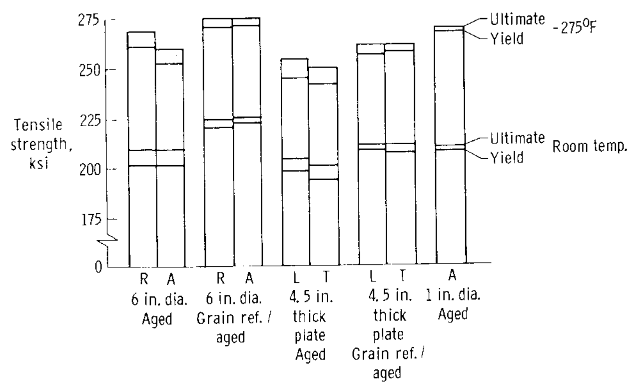

Fig. 8 Tensile properties of 18 Ni grade maraging steel at room and cryogenic temperatures.

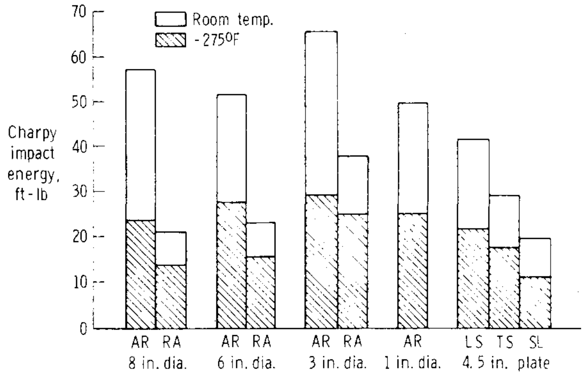

Fig. 9 Effect of orientation and product form on the Charpy impact strength of 18 Ni 200 grade maraging steel in the standard aged condition.

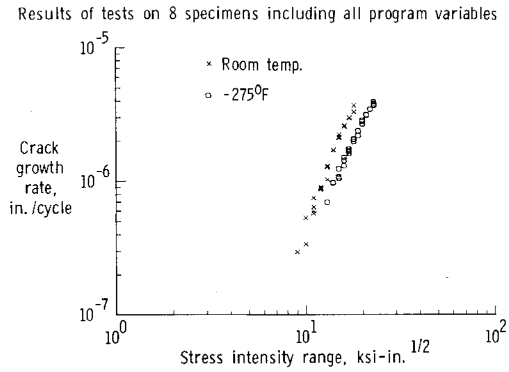

Fig. 11 Fatigue crack growth rates for 18 Ni 200 grade maraging steel at room and cryogenic temperatures.

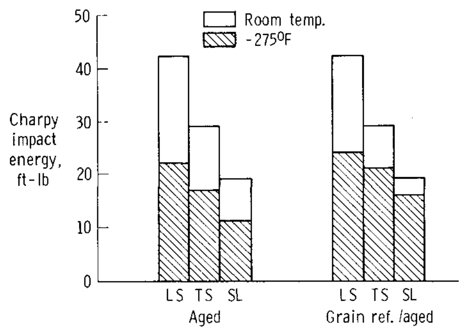

Fig. 10 Charpy impact strength of 4.5 in. thick plate in standard aged and grain-refined/aged conditions.

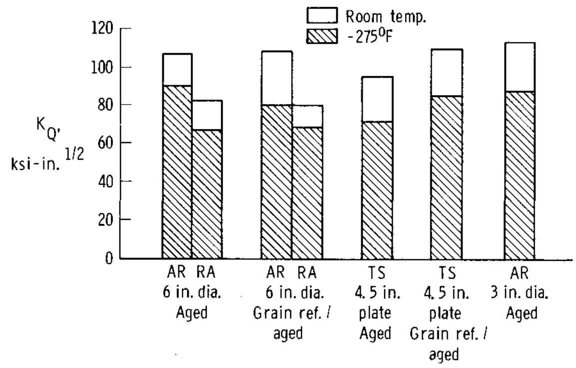

Fig. 12 Fracture toughness of 18 Ni 200 grade maraging steel at room and cryogenic temperatures.

uct forms and conditions are shown in Fig. 8 for both room temperature and $-275°F$ tests. Results are presented for bar stock 6 in. diam with specimens oriented in both the radial *R* and axial *A* directions and for 1 in. diam with specimens oriented in the axial *A* direction. For the 4.5 in. thick plate, specimens were oriented in the longitudinal *L* and transverse *T* directions. For both the 6 in. diam bar and 4.5 in. plate, the tensile properties were determined for grain-refined/aged as well as for standard aged material. The ultimate tensile strength was 200–225 ksi at room temperature and 250–275 ksi at $-275°F$ for all conditions tested. The 6 in. diam bar exhibited the highest tensile strength at each temperature. In all cases, the yield strength of the material was within 10 ksi of the ultimate tensile strength and the average reduction in area was 57% at room temperature and 52% at $-275°F$. Orientation had little effect on the tensile ultimate or yield strength for either the standard aged or grain-refined material. There was a significant improvement in the room temperature and cryogenic strength of the material when given the grain-refining heat treatment. The results of these tensile tests indicate that 18 Ni 200 grade maraging steel exceeds the design criterion of 150 ksi yield strength, which was established as a material requirement for $-275°F$ application regardless of heat treatment or specimen orientation.

Impact Testing

The results of the Charpy V-notch impact tests are shown in Figs. 9 and 10. Figure 9 illustrates the effects of specimen orientation and temperature on the impact behavior of specimens machined from 1–8 in. diam bar stock and 4.5 in. thick plate. There is a significant orientation effect on impact properties, particularly in the bar stock where specimens machined in the *AR* orientation exhibited superior impact behavior at room temperature and $-275°F$ compared to specimens machined in the *RA* orientation. There is also a significant reduction in the energy absorbed for specimens tested at $-275°F$. The percent reduction at $-275°F$ for specimens machined from bar stock is much less in the *RA* orientation as compared to the *AR* orientation. Similarly, the *SL* orientation in 4.5 in. thick plate showed the least reduction in energy absorbed at $-275°F$. The design criteria for materials to be used in the NTF specify a minimum impact value of 25 ft-lb at $-275°F$. It is apparent from Fig. 9 that the maraging steel is marginal with respect to this criterion for all product forms and specimen orientations. Figure 10 shows a comparison of the impact behavior achieved through standard aging with that achieved through the grain refinement/aging heat treatment for the 4.5 in. plate. The grain-refining heat treatment had no effect on the impact behavior at room temperature, but increased the energy absorbed at $-275°F$ for all orientations.

Fatigue Crack Growth Testing

Figure 11 is a composite plot of fatigue crack growth rate da/dN as a function of stress intensity ΔK and includes the results of eight specimens incorporating all of the experimental test variables. Examination of Fig. 11 shows that the fatigue crack growth rate at $-275°F$ is approximately half that at room temperature over the range of ΔK studied. In addition, since the plot for a given temperature incorporates all test variables, it appears that the fatigue crack growth rate of this material is insensitive to the metallurgical condition, specimen orientation, or product form. Although the fatigue crack growth rate was observed to be lower at $-275°F$ than at room temperature, the relatively high service stress levels for this cryogenic application suggest that this property must be take into account carefully to insure model structural integrity during cryogenic testing.

Table 2 Mechanical properties of 18 Ni 200 steel

Product form	Metallurgical condition	Temp, °F	σ_{ys}, ksi		σ_{ult}, ksi	
			R	*A*	*R*	*A*
Tensile strength						
Bar, in. diam						
6	Aged	Room	202	202	209	209
6	Aged	−275	261	253	268	260
6	Grain refined/aged	Room	221	223	224	226
6	Grain refined/aged	−275	271	272	275	275
1	Aged	Room	—	208	—	210
1	Aged	−275	—	268	—	270
Plate, in. thick			*L*	*T*	*L*	*T*
4.5	Aged	Room	197	194	204	202
4.5	Aged	−275	245	242	254	250
4.5	Grain refined/aged	Room	208	207	211	211
4.5	Grain refined/aged	−275	256	257	262	262

Product form	Metallurgical condition	Temp, °F	CVN, ft-lb		
Charpy impact strength					
Bar, in. diam			*AR*		*RA*
8	Aged	Room	58		21
8	Aged	−275	24		14
6	Aged	Room	52		23
6	Aged	−275	28		16
3	Aged	Room	66		37
3	Aged	−275	29		25
1	Aged	Room	50		—
1	Aged	−275	25		—
Plate, in. thick			*LS*	*TS*	*SL*
4.5	Aged	Room	42	29	19
4.5	Aged	−275	22	17	11
4.5	Grain refined/aged	Room	42	29	20
4.5	Grain refined/aged	−275	24	21	16

Product form	Metallurgical condition	Temp, °F	K_Q, ksi-in.$^{1/2}$		
Fracture toughness					
Bar, in. diam			*AR*		*RA*
6	Aged	Room	108		83
6	Aged	−275	91		66
6	Grain refined/aged	Room	109		80
6	Grain refined/aged	−275	80		69
3	Aged	Room	113		—
3	Aged	−275	90		—
Plate, in. thick				*TS*	
4.5	Aged	Room		95	
4.5	Aged	−275		71	
4.5	Grain refined/aged	Room		109	
4.5	Grain refined/aged	−275		88	

Fracture Toughness Testing

All fracture toughness tests conducted at −275°F were valid K_{Ic} tests according to the validity criteria outlined in ASTM E 399.[7] However, the majority of the tests conducted at room temperature exhibited plasticity effects and were not valid K_{Ic} tests. Figure 12 is a plot of fracture toughness K_Q for several product forms, orientations, and metallurgical conditions. The fracture toughness of the material was 80-113 ksi-in.$^{1/2}$ at room temperature and 66-90 ksi-in.$^{1/2}$ at −275°F. The effects of the temperature and specimen orientation on fracture toughness are similar to those on the impact strength. For example, there was a significant decrease in the fracture toughness when the specimens were tested at −275°F, although this percent decrease was not as large as the decrease observed on impact strength. Also, there was a decrease in fracture toughness values when specimens machined from bar stock were tested in the *RA* orientation. The grain-refining heat treatment improved the fracture toughness of specimens machined from the 4.5 in. plate at both room temperature and −275°F. No improvement, however, was observed in specimens machined from the 6 in. diam bar. Although many of the trends observed in the Charpy V-notch tests and fracture toughness tests were similar, no quantitative correlation was identified between the energy absoprtion values and fracture toughness. The 18 Ni 200 grade maraging steel appears to be marginal with respect to the minimum fracture toughness value of 85 ksi-in.$^{1/2}$ at −275°F specified in the cryogenic design criteria.

Conclusion

In this study, the mechanical behavior of 18 Ni 200 grade maraging steel was evaluated at room and cryogenic temperatures. Several wind tunnel model systems scheduled to be tested in the National Transonic Facility at cryogenic temperatures are currently being fabricated from this material. Because of the importance in maintaining structural integrity of model systems and structural components fabricated using this material, a program was undertaken to characterize material behavior for cryogenic applications. The effects of the experimental variables were evaluated using tensile, impact, fatigue crack growth, and fracture toughness testing. The results of these experiments have expanded the limited data base on material behavior at cryogenic temperatures, leading to the following conclusions:

1) The yield strength of 18 Ni 200 maraging steel at −275°F significantly exceeds the design criteria requirement of 150 ksi. However, fracture toughness and Charpy impact values determined at −275°F were either marginal or did not meet the cryogenic design criteria of 85 ksi-in.$^{1/2}$ or 25 ft-lb.

2) Trends in fracture toughness and Charpy impact behavior were similar and found to be independent on temperature, product form, and specimen orientation.

3) The fatigue crack growth rate of 18 Ni steel at −275°F is approximately half that at room temperature and appears to be insensitive to product form, specimen orientation, and metallurgical condition.

4) The room temperature elastic modulus of 18 Ni 200 grade maraging steel was statically determined to be 26.3×10^6 psi and is in close agreement with the manufacturer's reported value. The modulus was also determined at −100, −200, and −250°F and found to increase slightly with decreasing temperatures.

5) A grain refining heat treatment reduced the grain size of 18 Ni 200 grade maraging steel to one-tenth of the original grain size. The reduction in grain size increased the cryogenic tensile and impact properties and slightly enhanced the cryogenic fracture toughness.

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