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Fracture Toughness Characteristics of the New Weldable Steels of 180- to 210-Ksi Yield Strengths

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CONTENTS

Abstract	ii
Problem Status	ii
Authorization	ii
INTRODUCTION	1
MATERIALS	2
CHARACTERIZATION OF MATERIALS	2
METAL PROCESSING AND RESISTANCE TO FRACTURE	4
18Ni Steel	4
12Ni Steel	5
9Ni Steel	6
10Ni Steel	8
COUPLING OF APPARENT K_{Ic} STRESS INTENSITY TO DT ENERGY	9
EFFECTS OF MELTING PRACTICE ON FRACTURE TOUGHNESS	11
SUMMARY AND CONCLUSIONS	12
ACKNOWLEDGMENT	13
REFERENCES	14
APPENDIX A – Production Experience, Melting Practices, and Compositions of 18Ni, 12Ni, 9Ni, and 10Ni Ultrahigh-Strength Steels	16
APPENDIX B – Tensile Characteristics of 180- TO 210-ksi Yield-Strength Steels as Influenced by Heat Treatment	20
APPENDIX C – Summary Data of Melt Practice, Heat-Treatment Conditions, Tensile Properties, and Dynamic Tear Energy for 18Ni, 12Ni, 9Ni, and 10Ni High-Strength Steels	22

ABSTRACT

The yield strength range for steels from 180 to 210 ksi is currently covered by four weldable alloys of the following nominal chemical analysis: 18%Ni-8%Co-3%Mo maraging steel, 12%Ni-5%Cr-3%Mo maraging steel, 9%Ni-4%Co-0.20%C quenched and tempered (Q&T) steel, and 10%Ni-8%Co-2%Cr-1%Mo-0.10%C Q&T steel. Broad ranges of fracture resistance have been reported for these materials based on various fracture tests, and this report presents information for material selection and design guidance by providing an analysis of the interactions between the metallurgical and mechanical parameters that contribute to the fracture resistance of plate products. Definitions of the interaction between the metallurgical and the mechanical aspects are developed with the use of the Dynamic Tear (DT) test and the Ratio Analysis Diagram (RAD), where a close correlation between K_{Ic} values and DT energy values is extended to include materials of high fracture toughness. Limited use was made of the Charpy-V-notch test after it was shown to be unreliable for fine definitions of fracture toughness for these ultrahigh-strength steels. Materials produced from alloys melted under atmospheric air and by various vacuum melting practices were included; metallurgical factors investigated, in addition to melting practice, were rolling procedure and heat treatment.

Steels in the yield strength range from 180 to 210 ksi are at the midpoint of the "strength transition," which starts from a potentially high level of fracture resistance and drops to a low level of fracture resistance. The dramatic falloff in fracture toughness is also evidenced by the fracture appearance in the 1-in. DT specimens which changes from large, plastic, enclave-type fracture for the best steel at 180 ksi yield strength to a mixed-mode type fracture for the best steel at 210-ksi yield strength. Chemical composition has a direct effect on yield strength, but other factors, mainly purity of the metal, control fracture resistance. All air-melted materials in the 180- to 210-ksi yield strength range are brittle (plane strain properties) in sections exceeding 1 in. in thickness. Vacuum melting significantly improves fracture resistance, and the order for increasing effectiveness is single vacuum-arc remelting, vacuum-induction melting, and double vacuum melting. By optimizing metal processing procedures, material at 180 ksi yield strength can resist fracture initiation at all elastic stress levels in thick sections as long as hardenability limits are not exceeded, while material at 210 ksi yield strength can resist plane strain fractures only in sections of approximately 2 in. even in the absence of metallurgical gradients from the surface to the midthickness position.

PROBLEM STATUS

This report completes one phase of the problem; work on other phases is continuing.

AUTHORIZATION

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FRACTURE CHARACTERISTICS OF THE NEW WELDABLE STEELS OF 180- TO 210-KSI YIELD STRENGTHS

INTRODUCTION

In the past decade, considerable emphasis has been placed on the development of structural metals featuring high strength-to-density ratios. New families of heat-treated steels have been developed, and several alloys with yield strengths ranging from 160 to 300 ksi can now be procured to ASTM specifications (1). With this rapidly expanding technology and the marketing of new materials at higher yield strengths, more attention has been focused recently on improving resistance to fracture and on the definition of factors relating to the expected performance of welded structures. Although welded fabrication with steels at 80 to 100 ksi yield strength became commonplace in the past decade, it is only within the past two years that similar fabrication with 130- to 140-ksi yield strength steels has become a distinct reality (2). The next step for structural utilization of still higher yield strength steels in large welded structures is aimed at the 180- to 210-ksi range.

Difficulties in the interpretation of results obtained with a wide variety of fracture toughness test methods have complicated the problem of selection of options in the application of these steels to novel engineering structures. Fortunately many of these difficulties have now been overcome, as will be described. In addition, it has become evident that the influence of metal processing operations such as melting and rolling can overshadow the effect of chemical composition on fracture resistance. A comparison of compositional effects must therefore be conducted with materials produced to specific quality levels with respect to metal purity and the content of nonmetallic phases. Another feature which amplifies the problem of comparing steels at 180 to 210 ksi yield strength is that these materials lie in the yield-strength range which has been termed the "strength transition." In the strength transition region, small variations in yield strength such as 10 ksi, which is only 5 percent of the yield strength, can result in highly significant changes in fracture resistance.

The approach used in this investigation to clarify the relative influence of metallurgical factors and mechanical factors was to evolve a spectrum view of all parameters of influence. The clarification of the coupling between the metallurgical and mechanical aspects is greatly facilitated by the use of the Ratio Analysis Diagram (RAD) (3). This new RAD concept developed by Pellini provided the first method for integrating and defining these interactions. By the use of the RAD, the engineering benefits derived from increased resistance to fracture are relatable to alloying or to improvements in metal quality at any level of yield strength.

The RAD provides a graphical method by which the fracture resistance of structural metals may be indexed by the results of various test methods for measuring fracture toughness. The RAD is zoned by selected K_{Ic}/σ_{ys} ratio lines, which provide regimes of increasing fracture resistance. Although formal analytical relationships for critical flaw sizes involve the square of the K_{Ic}/σ_{ys} ratio, linear ratio values are indicative of a specific level of fracture resistance. Using this ratio, a detailed interpretation of performance in terms of flaw-size-vs-stress conditions for fracture can be obtained from fracture mechanics equations or charts (3). In discussions of the data to be presented, the significance of the K_{Ic}/σ_{ys} ratio values relative to flaw-size-vs-stress conditions for fracture will be described.

MATERIALS

Four alloys were included in this study: 18%Ni-8%Co-3%Mo maraging steel, 12%Ni-5%Cr-3%Mo maraging steel, 9%Ni-4%Co-1%Cr-1%Mo-0.20%C quenched and tempered (Q&T) steel, and 10%Ni-8%Co-2%Cr-1%Mo-0.11%C Q&T steel. For brevity, these steels will be referred to simply as 18Ni, 12Ni, 9Ni, and 10Ni steel, respectively, which is the chronological order of their development. Only summary metallurgical considerations are discussed in the text, and emphasis is placed upon mechanical characterizations. Details concerning the metallurgical aspects, data pertaining to the pedigree of the materials, and test data are provided as summaries.

The four steels included in this report were developed during the 1960's, and production experience varies with each material. Details concerning production experience, chemical composition, and metal processing conditions are presented in Appendix A. A discussion of the physical metallurgy aspects and the influence of heat treatment on tensile characteristics is presented in Appendix B. Details concerning heat size, heat-treatment condition, tensile properties, and dynamic-tear energy data are given in Appendix C. All data discussed in the text have been obtained from material produced in the form of 1-in.-thick plate.

CHARACTERIZATION OF MATERIALS

The Ratio Analysis Diagram (RAD) concept for characterizing the mechanical performance of high-strength metals was evolved during the period from 1962 to 1968. These diagrams provided the first full spectrum view of the relationship between fracture toughness and yield strength for ferritic steels. The initial RADs were referenced to structural performance in Explosion Tear Tests (ETT) with laboratory fracture toughness index scales for Charpy-V-notch (C_v) energy and Dynamic-Tear (DT) energy (4). In these early diagrams, the upper bound of the fracture toughness–yield strength relationship was called the Optimum Materials Trend Line (OMTL). Since the OMTL represented the state of the art at the time of publication, it has subsequently been redefined as the Technological Limit (TL) line.

When the studies were concentrated on steels in the 180- to 210-ksi range of yield strength, all three laboratory tests for fracture toughness–DT, critical stress intensity (K_{Ic}), and C_v–were conducted with the hope that a correlation for the various test results would be developed. A close correlation between DT energy and K_{Ic} values was developed, but only a "broadband" qualitative correlation was developed for C_v and DT values, which was reported in early investigations (4). Further analysis of experiments with materials in a narrow range of yield strengths indicated that the C_v specimen did not provide consistently reliable and "fine" definitions of fracture toughness. For example, the relative insensitivity of the C_v test to variations in fracture toughness of 18Ni steel is illustrated in Fig. 1, where C_v and DT energy values are compared for the purpose of evaluating the influence of vacuum melting on resistance to fracture. On the basis of the C_v test, only a slight improvement, 30 to 46 ft-lb, was achieved from melting under vacuum. However, when fracture toughness was determined with a more definitive test method, a highly significant improvement in fracture resistance was observed for the material melted under vacuum; the DT energy values increased from 700 to 4600 ft-lb with vacuum melting. This increase in DT energy was further emphasized by a dramatic change in fracture appearance from relatively brittle (flat) fracture to a highly ductile (full slant) fracture. Because of the unfavorable performance of the C_v test in this and other similar comparisons of C_v and DT test results, no additional C_v energy values are reported here, and only results from the DT test and the K_{Ic} test are used because of the superior reliability of these two test methods.

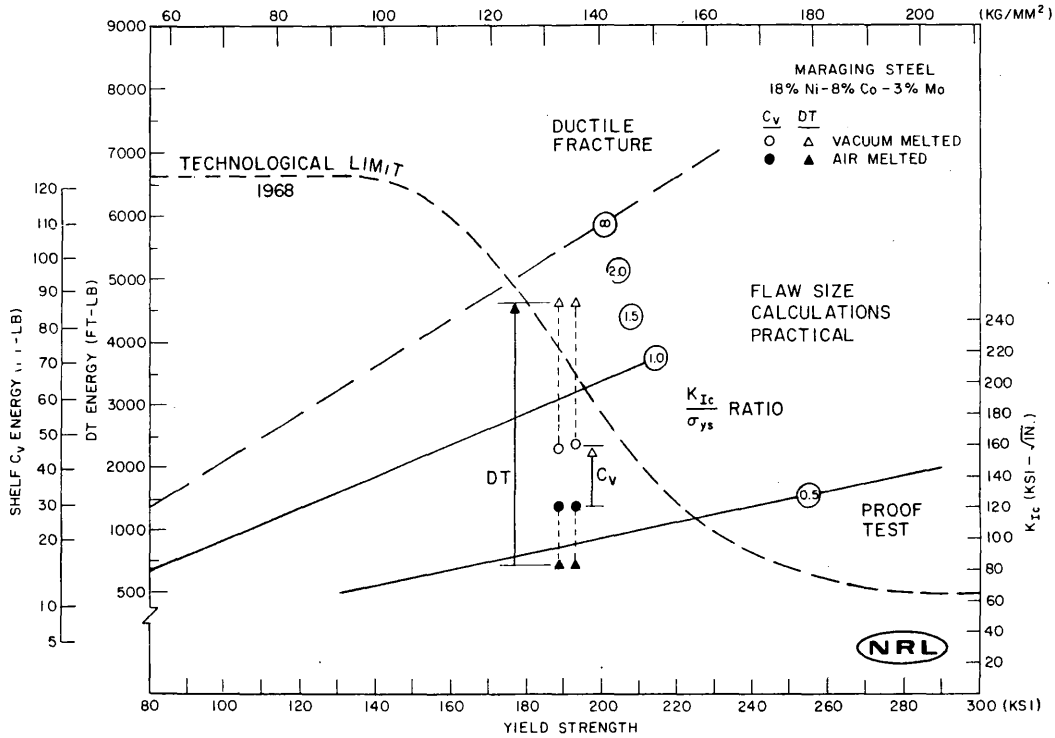

Fig. 1 - RAD definition of the influence of vacuum melting on the fracture resistance of 18Ni steel as determined by DT and C_v test methods. Fracture-toughness characterization by the DT test indicates air-melted material to be brittle ($K_{Ic}/\sigma_{ys} < 0.5$) and vacuum-melted material to be ductile ($K_{Ic}/\sigma_{ys} \approx 1.5$), while the C_v test shows only a slight improvement ($K_{Ic}/\sigma_{ys} \approx 0.6$ to 0.8) for the air-melted and vacuum-melted material, respectively.

The best estimate of the upper bound for interpretation of structural performance based upon linear, elastic, fracture mechanics regardless of section thickness is indicated in Fig. 1 by the K_{Ic}/σ_{ys} line labeled "∞." This upper bound estimate is considered to be optimistic, and results based on thick section tests (5,6) indicate that the ∞ line cannot be placed at a higher level. It is possible that additional research on this question may indicate a slightly lower relative position. For materials which lie above this "infinity" ratio line, plastic instability is the only mode for fracture, and overload stress levels (P/A engineering stress) above yield strength are required for propagation.

Materials are not required to lie above the infinity line (plastic resistance to fracture) on the RAD to provide for a fracture-safe design concept. A high level of performance is also indicated for a finite ratio when the size of a critical flaw is larger than the section thickness. In this case "brittle" fracture cannot initiate, since local plastic overload is required to cause a crack to become unstable. However, if a fracture is initiated from a local plastic overload, the same high level of resistance to propagation is not assured, as it is for material which lies above the infinity ratio line.

Although, in principle, fracture must occur at elastic stress levels for fracture mechanics principles to apply, Kies has developed a technique for extending the measuring capabilities of specimens loaded in bending even though fracture initiates at stress levels above the yield strength (7). The relation between K_{Ic} values determined with this technique and DT energy values is discussed in a later section of this report.

METAL PROCESSING AND RESISTANCE TO FRACTURE

18Ni Steel

The maraging steels were the first of the new, ultrahigh-strength steels, and they have been produced by four different melting practices. The four practices are air melting, vacuum-arc remelting (VAR), vacuum-induction melting (VIM), and double vacuum melting (VIM & VAR). Since steels in the 18Ni family are capable of attaining yield strengths above 300 ksi, this alloy provides a view of the influence of melting practice over a broad range of yield strength.

The RAD for 18Ni steels is shown in Fig. 2, where an analysis of the influence of melting practice on resistance to fracture can be readily developed. It can be seen that air-melted materials lie below the K_{Ic}/σ_{ys} ratio line of 0.5 for all levels of strength above 180 ksi. The 0.5 ratio line indicates a lower bound of fracture safety based upon reliable detection of subcritical flaws with current nondestructive inspection techniques. Use of materials below this line requires "zero defect" design and a proof test to ensure any safe life period. Vacuum melting significantly improves fracture resistance, and the improvement in fracture toughness due to the improved cleanliness achieved by vacuum melting is apparent especially in the 180- to 190-ksi yield strength range. Note that at the 180-ksi yield strength level, melting practice changes the material performance from the "proof test required" category to a level where fracture initiation at elastic stress levels is no longer possible even for flaws residing in sections thicker than 2.5 in., i.e., the K_{Ic}/σ_{ys} ratio = 1.0 (Ref. 3).

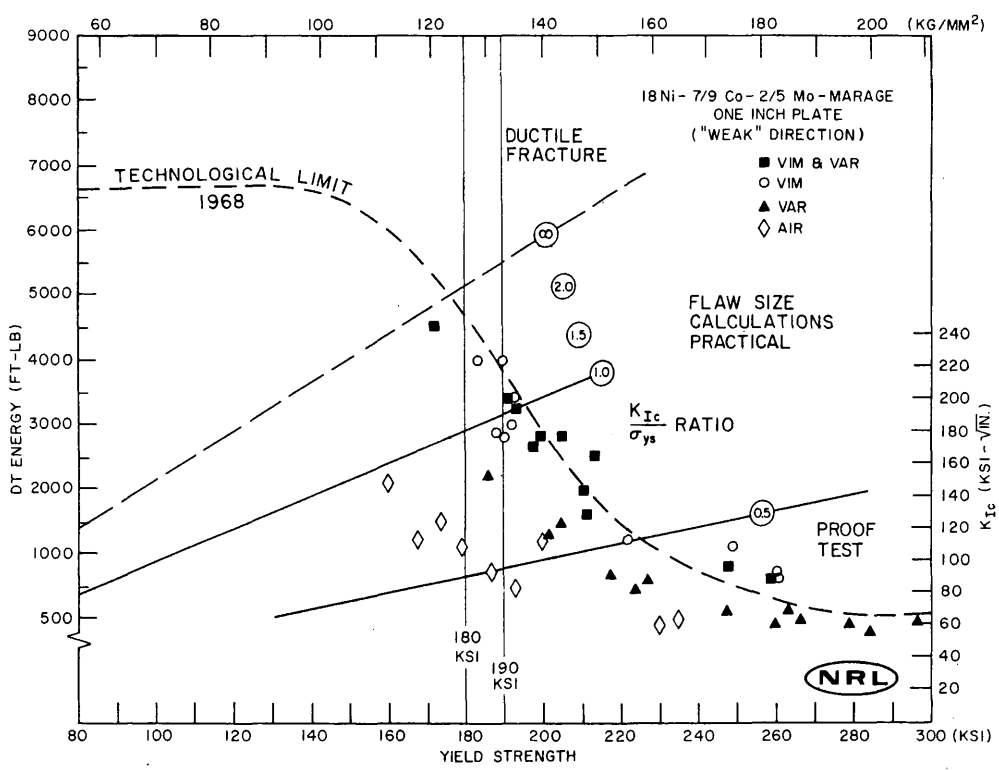

Fig. 2 - RAD definition of the influence of melting practice on the fracture characteristics of 18Ni maraging steels

The 18Ni steels essentially define the TL line for steels above the yield strength level of 200 ksi. Changing the processing procedures for these ultrahigh-strength materials does not appear to result in the remarkable improvements in fracture toughness as noted for materials in the 180-to 190-ksi yield strength range. Although fracture toughness levels were not elevated above the 0.5 ratio line, relative improvements from vacuum melting are significant and only premium processing conditions should be considered for these brittle materials.

12Ni Steel

The RAD illustrating the influence of melting practice on resistance to fracture for the 12Ni steels is shown in Fig. 3. Optimum heat treatment was required to attain yield strength levels in the 180- to 190-ksi range, and it can be noted that a variation in yield strength of only 10 ksi can result in a significant change in fracture toughness because these materials lie within the strength transition. Also, the low position on the RAD indicates that air-melted 12Ni material is brittle (fracture propagation at elastic stress levels possible) in sections greater than 1 in. thick. At least a VAR practice is required to provide material with a level of fracture toughness which precludes the initiation of plane strain fractures in 12Ni steel sections over 1 in. thick. With the additional refinement of using the VIM melting practice, 12Ni steel attained very high levels of fracture toughness, and it assisted in defining the 1968 TL line.

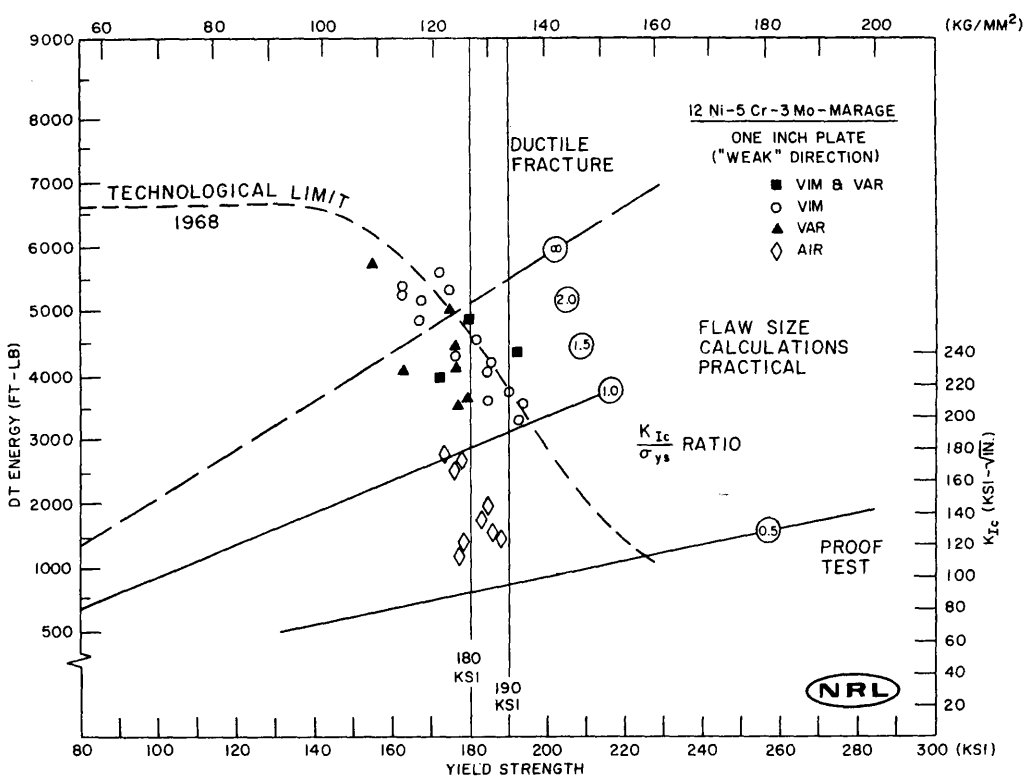

Fig. 3 - RAD definition of the influence of melting practice on the fracture characteristics of 12Ni maraging steel

9Ni Steel

The mill heat treatment for the 9Ni plate products in this investigation consisted of normalizing at 1650°F, austenitizing at 1550°F, water quenching, and double tempering at 1000°F (2 + 2 hr, air cooled). Following a more recent recommendation, samples were also tempered, 4 to 8 hr at 1025°F, to develop an optimum fracture toughness–yield strength relationship. In addition, samples were tempered for prolonged periods at 950°F and 1025°F, simulating stress-relief heat treatments which might be considered during forming operations or after welding.

Fracture toughness of "as received" material was determined for temperatures ranging from -120° to +120°F. One of the two large plates produced for this investigation was cross-rolled at essentially a 1:1 ratio, while the other plate was round-rolled in order to minimize anisotropy normally developed in conventionally rolled, large plates. Both rolling techniques developed isotropic fracture toughness properties as indicated by the data in Fig. 4. However, fracture toughness-temperature characteristics were different for the two materials in that a shelf position (maximum possible) was attained at 30°F for the cross-rolled plate, but a shelf position was not reached until 80°F for the round-rolled plate. From the standpoint of shelf-level fracture resistance, the more expensive round-rolling processing did not appear to improve performance.

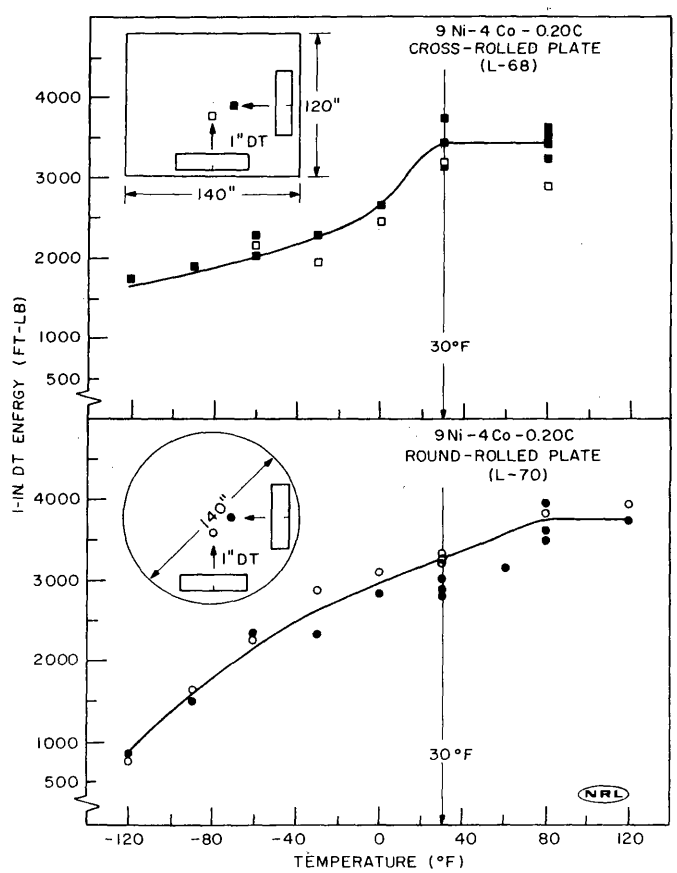

Fig. 4 - Illustrating the transition temperature aspects on the fracture resistance of 9Ni steel. Top, relationship from large, 1-in.-thick, cross-rolled plate. Bottom, relationship from large, 1-in.-thick, round-rolled plate.

The mode of fracture propagation in the DT specimen shown in Fig. 5 reflects the change in fracture toughness with decreasing temperature. At temperatures corresponding to shelf energy levels, 30° and 80°F for the respective plates, fracture propagated in a mixed mode, and the percent of slant-type fracture decreased at lower temperatures. It should be noted that these characteristics represent the first information reported for "large" (120- × 140-in.) plates in 9Ni steel. All previous plate-metal evaluations of 9Ni steel have been based on highly cross-rolled plates generally no larger than several square feet in size.

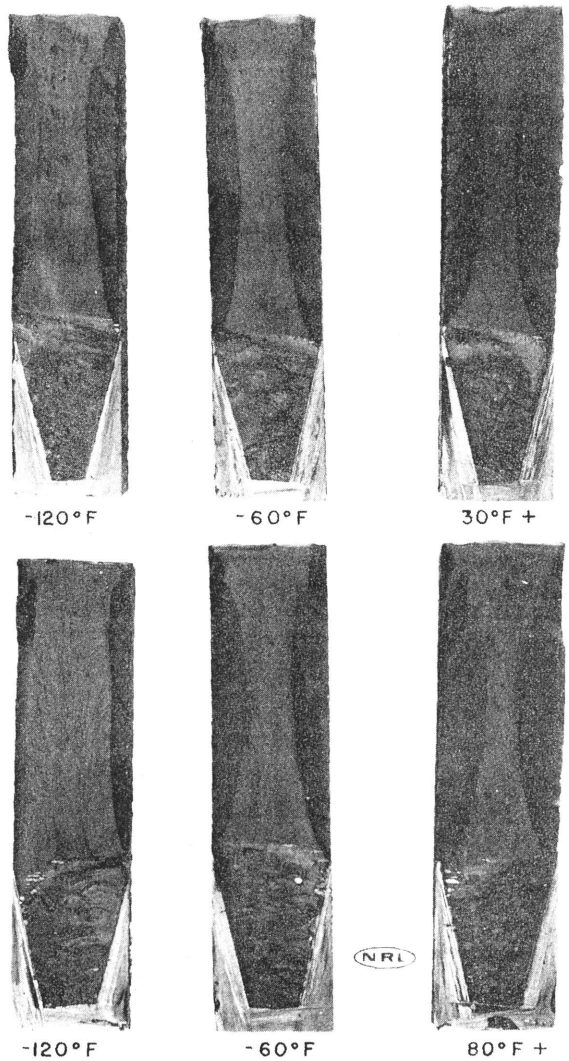

Fig. 5 - Illustrating the change in macrofracture appearance in 9Ni steel as the result of the temperature transition. Top series are dynamic tear specimens from 1-in.-thick, 1:1 cross-rolled plate. Bottom series are dynamic tear specimens from 1-in.-thick, round-rolled plate.

The RAD positions of 9Ni steel heat treated under the various conditions are shown in Fig. 6. It is apparent that 9Ni steel develops a comparatively high DT–yield strength relationship, approaching the 1968 TL line. The yield strength for material in the mill Q&T heat-treatment condition ranged from 179 to 186 ksi. Prolonged holding at 950° or 1025°F resulted in only a slight decrease in yield strength and a corresponding increase in DT energy following the slope of the TL line. It should be noted that no samples of 9Ni steel melted with VIM or VIM and VAR practices were available at the time of this investigation; accordingly, no comparisons of melting practices can be made. The data relate to the standard melting practice used for commercial production of 9Ni steel, i.e., a single VAR.

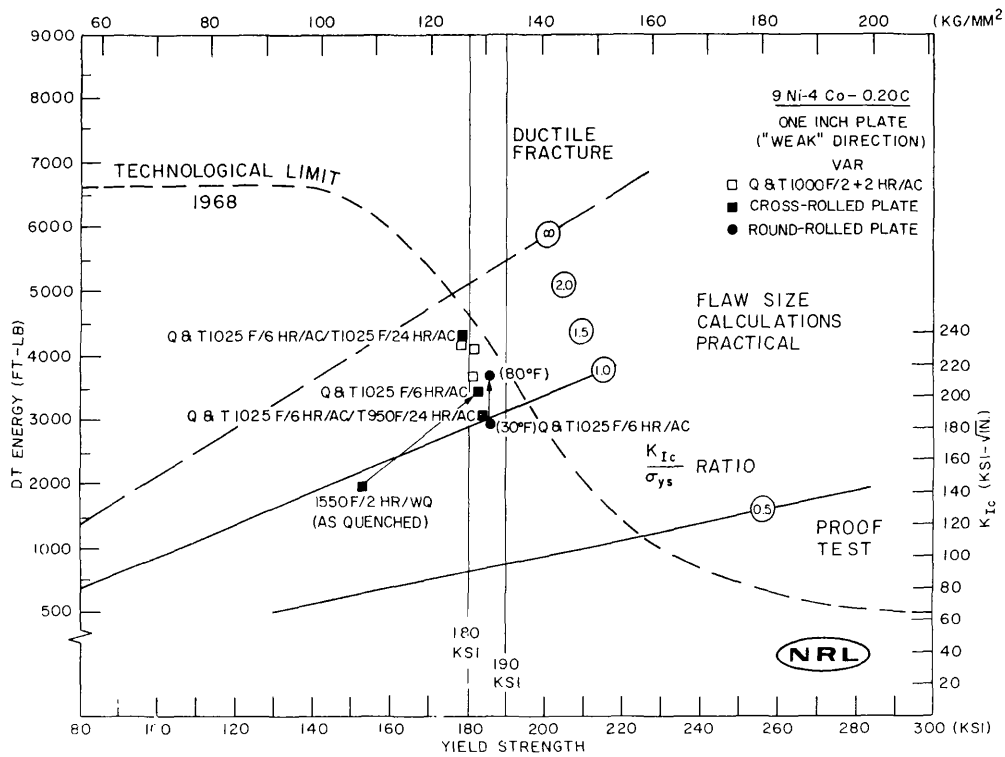

Fig. 6 - RAD definition of the influence of tempering heat treatment on the fracture characteristics and yield strength of 9Ni steel

10Ni Steel

The recommended heat treatment of the 10Ni steel plates consists of austenitizing at 1500°F, water quenching, tempering at 950°F, and water quenching. The recommended time at the tempering temperature is 5 to 16 hr depending on plate thickness. Studies concerning the influence of heat treatment on properties included longer holding times at 950°F, other austenitizing temperatures, and tempering at 900°F.

The influence of heat treatment on the fracture characteristics of 10Ni steel can be seen by the RAD position of the various materials, Fig. 7. The first striking observation is the exceptionally high DT energy values exhibited by the 10Ni material, which was tempered at 950°F. For this heat-treatment condition, the DT energy values are positioned above the 1968 TL line in the yield strength range of 160 to 190 ksi. When tempered for

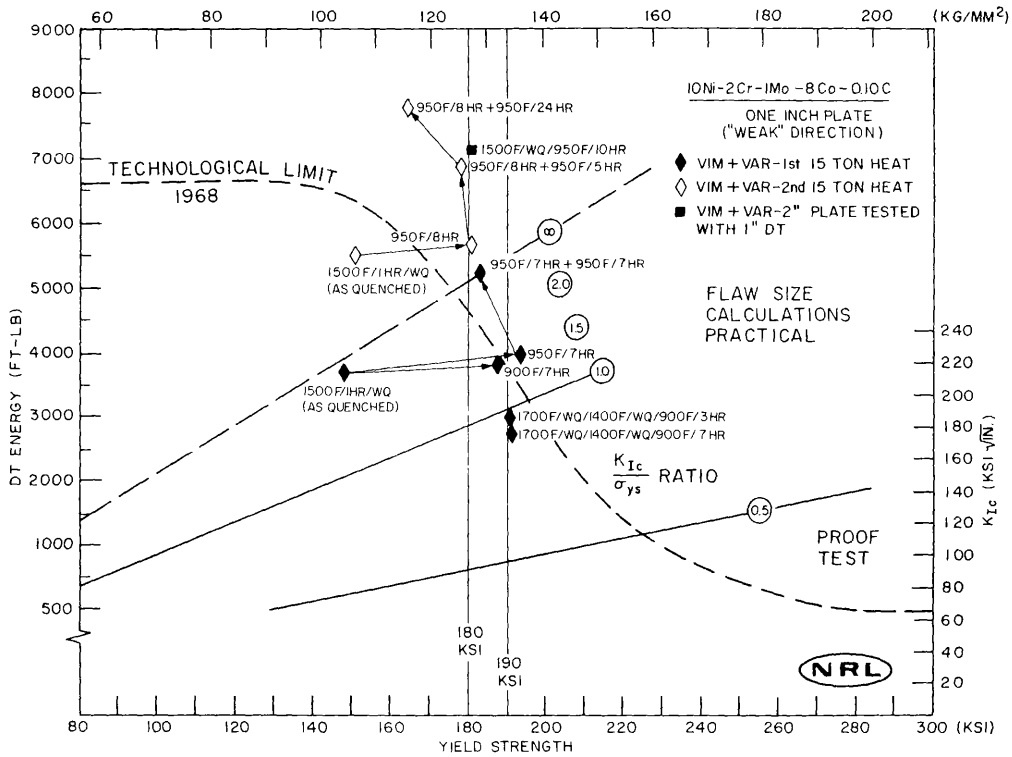

Fig. 7 - RAD definition of the influence of tempering heat treatment on the fracture characteristics and yield strength of 10Ni steel

8 hr at 950°F, material from the first 15-ton heat developed a 190-ksi yield strength, while that from the second heat developed only a 180-ksi yield strength. Prolonged holding at 950°F resulted in a reduction in yield strength, 10 to 20 ksi, with a dramatic increase in toughness, greater than would be expected from the slope of the 1968 TL line. When tempered at 900°F, first-heat material also developed approximately 190-ksi yield strength, but fracture toughness appeared to be slightly lower than that developed after a 950°F temper. The benefits obtained from improved metal processing can be readily evaluated in terms of the high level of structural performance indicated by a position on the RAD above the infinity ratio line; in fact, the 10Ni steel, which had been VIM & VAR melted, shifts the TL line for 1969 upward in the 180- to 190-ksi yield strength range.

COUPLING OF APPARENT K_{Ic} STRESS INTENSITY TO DT ENERGY

The K_{Ic} scales in the RADs shown previously were indexed by a K_{Ic}–DT correlation observed for a wide variety of steels in the product form of 1-in.-thick plates (3). Fracture mechanics specimens of the single-edge-notched (SEN) tensile type were used to determine the K_{Ic} values for the initial correlation. Side-grooving to a depth of 5 percent of plate thickness was occasionally employed, and test conditions generally conformed to the recommended ASTM method of testing for plane-strain fracture toughness.

More recently, K_{Ic} data from a variety of specimen types have become available, and one popular specimen is the precracked bend specimen. Stonesifer and Smith (8) have reported K_{Ic} stress-intensity values for the same 180- to 210-ksi yield strength steels included in this investigation using precracked-bend, bar specimens and analysis techniques recommended by Kies (7). This method provides an adjustment or correction

for the large plastic strains which develop in undersized specimens. A valid K_{Ic} value is considered to be independent of specimen size when the specimen is of the prescribed minimum thickness, which ensures that instability fracture occurs at loads providing nominal stress levels below yield strength. However, when properly corrected, "apparent" K_{Ic} values obtained from undersized specimens are considered to provide useful plane-strain fracture toughness values.

The precracked-bend, bar specimen favored by Kies was designed to require a minimum of material and precision machining and to provide for easy K_{Ic} measurements in any one of four major orientations (WR, WT, RW, and RT) with respect to the rolling direction. A notch is machined to a depth of 20 percent, which is then extended with a fatigue crack to a total notch depth of approximately 25 to 30 percent of the bar depth. Side grooves with a depth of 5 percent of the thickness are used on all specimens.* For materials of high fracture toughness, 15 or more iterations are required to provide a fully corrected K_{Ic} value, which may be 25 to 50 percent higher than the uncorrected K_{Ic} value.

Figure 8 presents a summary of the DT-K_{Ic} data for these 180- to 210-ksi yield strength steels. The location of a given steel in the RAD is compared for entry from each respective scale; the DT energy (solid symbol) is joined by a vertical line to the corrected K_{Ic} value (open symbol) for each respective material. It is apparent that a RAD index, provided by the corrected K_{Ic} values, is in good correspondence with DT energy values provided by the RAD location. It is also evident that the strength transition aspects previously described on the basis of DT energy are also evidenced by results from the K_{Ic} test method.

The problems of anisotropy on fracture toughness in rolled plates have been emphasized by NRL investigators since the studies of ship steels in the early 1950's (11). For this reason, the original K_{Ic}-DT correlation was based on results of DT and SEN tests conducted with both specimens oriented in the same rolling direction. Most of the DT data shown in Fig. 8 represent resistance to fracture in the "weak" (WR orientation) direction. Generally, when both K_{Ic} and DT values were obtained for the same WR orientation, the correspondence was within 10 to 15 ksi $\sqrt{\text{in.}}$ For the few steels which show large differences (> 30 ksi $\sqrt{\text{in.}}$) in RAD location of DT and K_{Ic} points, the K_{Ic} values were obtained from specimens in the RT or WT orientation. Fracture in the RT or WT orientation can be interrupted by ordered arrays of inclusions or laminations, and higher apparent K_{Ic} values would be expected from specimens having these orientations.

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*Apparent K_{Ic} values were calculated using the equation published by Kies and others (9). The equation may be written as

$$K_{Ic} = 2.060 \frac{PL^1}{BD^{3/2}} \left[\frac{1}{\left(1 - \frac{a}{D}\right)^3} - \left(1 - \frac{a}{D}\right)^3 \right]^{1/2}$$

in which P is load, L^1 is moment arm length, B is specimen width perpendicular to load application, D is specimen depth (parallel to load application), and a is initial crack depth. The constant 2.060 was empirically obtained as a best fit for the existing data. The equation incorporates a best fit for the compliance data of Irwin, Bird, Gross, and Romine. Use of this equation eliminates the need for obtaining a calibration or compliance curve. In the absence of "pop-in" on the load deflection curves, the ultimate load is substituted for P in calculating the apparent K_{Ic} value. The Irwin (10) plastic zone correction to the crack length for plane strain conditions, r_y, was calculated from the equation

$$r_y = \frac{1}{6\pi} (K_{Ic}/\sigma_{ys})^2,$$

where σ_{ys} is the tensile yield strength of the material.

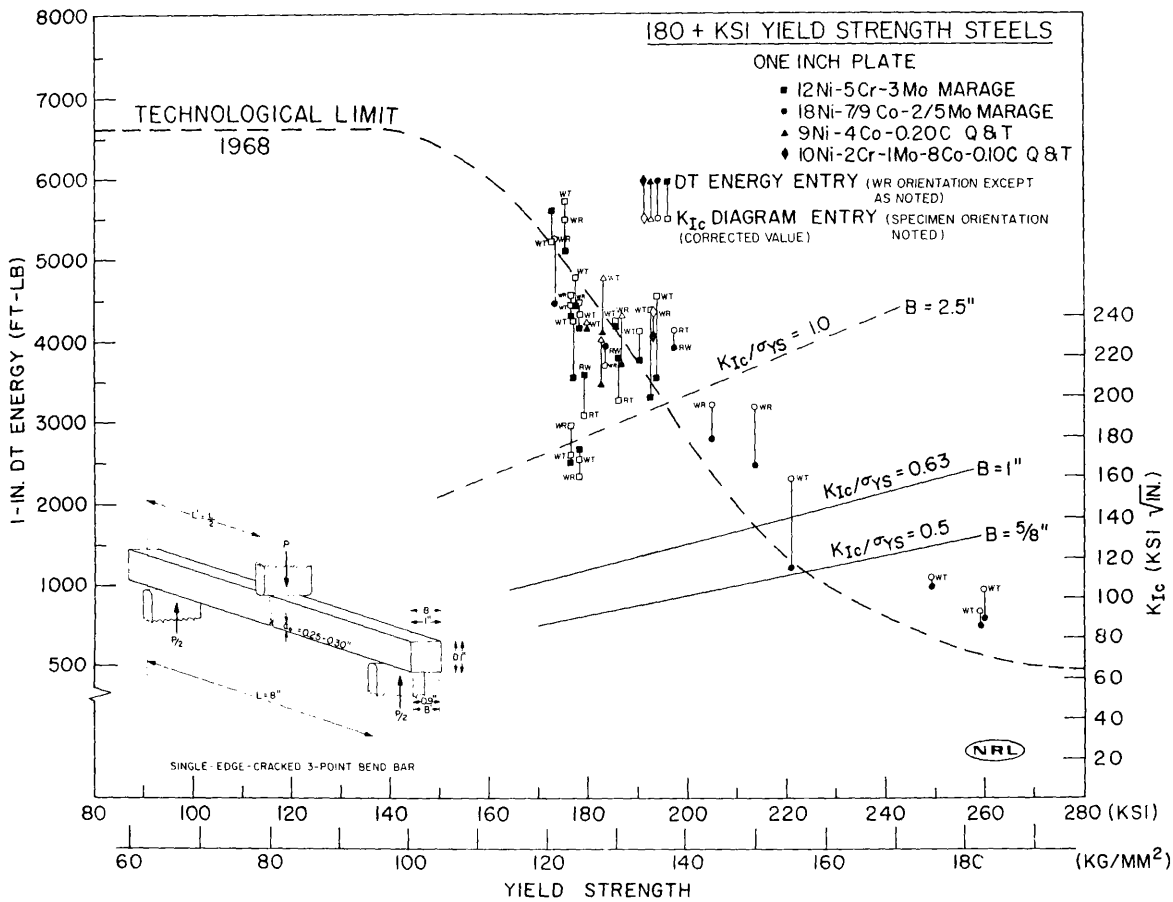

Fig. 8 - Comparison of dynamic-tear energy and apparent K_{Ic} values for indexing ultrahigh-strength steels to the Ratio Analysis Diagram. The K_{Ic} values have been corrected in accordance with Kies' formula (7).

EFFECTS OF MELTING PRACTICE ON FRACTURE TOUGHNESS

Melting and processing operations impart certain intrinsic characteristics or qualities to the metal which are retained in the finished product. The enhanced fracture toughness shown for the 180- to 210-ksi yield strength steels with increasing sophistication of melting practice is primarily the result of decreasing the amount of impurities. Purification has a direct effect on the fracture process involving microvoid coalescence. Microvoid coalescence is the microfracture mode for fracture throughout the strength transition; the cleavage microfracture mode is not involved in the strength transition. The microvoid coalesence process involves the plastic straining of patches of grains (located between microvoids) that originate from inclusions, cracking of hard phases, or other impurity element phases. Reducing the number and size of impurity particles permits the crack-tip plastic zone to increase in size before complete coalescence or macrofracture occurs, and therefore cleanliness has a great effect on resistance to the ductile, tearing type of fracture (12).

SUMMARY AND CONCLUSIONS

The state of the art with respect to commercial availability in plate form of ultrahigh-strength steels is essentially defined by the results of this investigation. By including materials melted and processed under a variety of production conditions, the effects of chemical composition, yield strength, melting practice, heat treatment, and rolling practice on resistance to fracture were established. Analyzing and illustrating the effects of these many factors on structural performance in terms of critical flaw sizes and stress levels would have been an involved and complicated procedure without the assistance of the RAD. The interactions between the various mechanical and metallurgical factors that affect the rank and usability of specific materials are displayed in simple engineering terms in the RAD; this wealth of information is indexed to fracture toughness values obtained with either the Dynamic Tear test or the plane strain fracture mechanics test.

For the four generic steels, 18Ni, 12Ni, 9Ni, and 10Ni, included in this investigation, chemical composition had a direct effect on yield strength, but other factors controlled fracture resistance. The intrinsic fracture resistance of all steels decreased sharply in the yield strength range of 180 to 210 ksi which is termed the "strength transition," but the intrinsic level of fracture toughness at a specific yield strength is primarily dependent upon the quality or cleanliness of the material in a particular product. Melting practice, therefore, is a most important processing variable to be considered when use of ultrahigh-strength steels is contemplated.

The results of this study emphasize several important features of the fracture characteristics of ultrahigh-strength steels in thick sections, and the following conclusions are warranted.

1. The yield strength level has a very large effect on fracture resistance in the range of the "strength transition." In this range, a 10-ksi shift in yield strength can result in a very significant change in the level of fracture resistance. Steels at all degrees of metallurgical quality in the yield strength range from 180 to 210 ksi are at the midpoint of the strength transition, and increasing the metallurgical quality by the use of improved melting practices tends to steepen the transition. These features are summarized on the RAD in Fig. 9 showing those fractures of 10Ni and 18Ni DT specimens for steels melted by VIM and VAR processes that define the 1969 Technological Limit in this yield strength range. The dramatic fall-off in fracture toughness in the range of 180- to 210-ksi yield strength is evidenced by the steep slope in the Technological Limit line and also by the fracture appearance of the DT specimens, which changed from a large, plastic enclave type for steel at 180 ksi yield strength to a mixed-mode type for steel at 210-ksi yield strength.

2. All air-melted materials in the 180- to 210-ksi yield strength range are brittle (plane-strain properties) in sections over 1 in. thick. Vacuum melting significantly improves the resistance to the initiation of fracture in steels at all yield strength levels. Improvements from vacuum melting are summarized in Fig. 10, where the order for the effectiveness of melting practice to improve metal quality appears to be AIR, VAR, and VIM + VAR. The influence of melting practice on fracture toughness appears to decrease with the increase in yield strength, as noted by the decrease in slope of the bands. This is unfortunate because the level of structural performance with respect to fracture resistance is dependent upon maintaining a high value for the K_{Ic}/σ_{ys} ratio. The best material at 180 ksi yield strength can resist fracture initiation at all elastic stress levels in thick sections as long as hardenability limits are not exceeded, while the best 210-ksi yield strength material can resist plane-strain fractures in sections only up to approximately 2 in. thick even in the absence of metallurgical gradients from surface to midthickness positions.

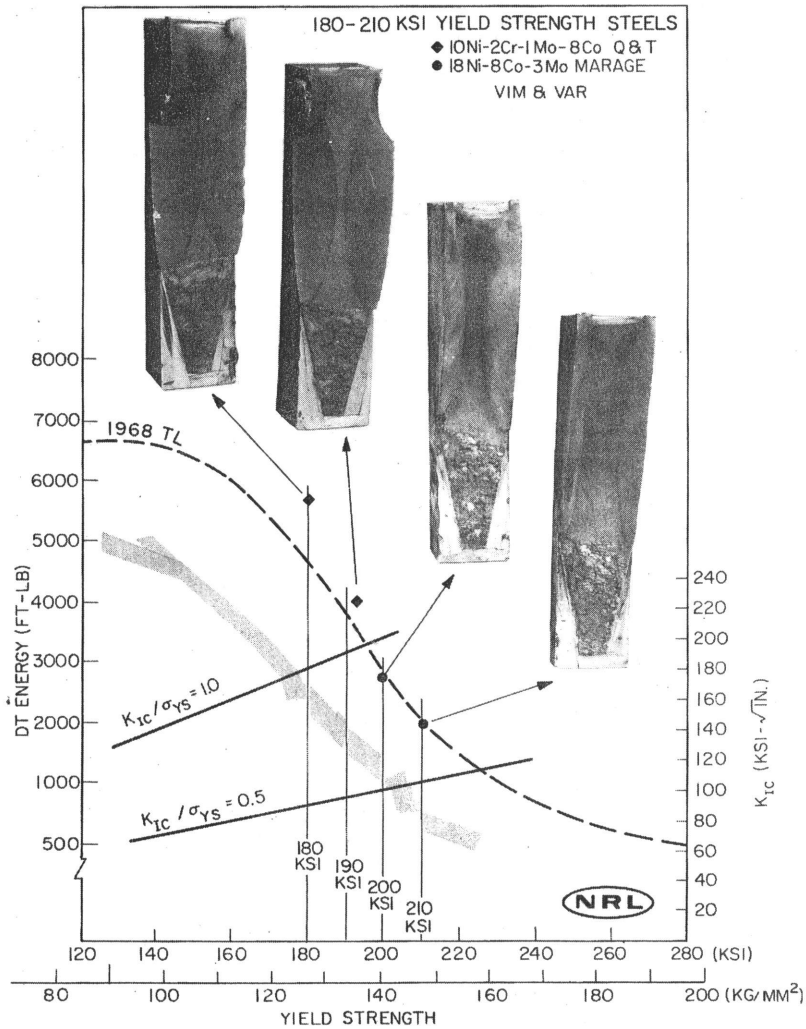

Fig. 9 - RAD definition of the sharp decrease in fracture toughness for optimum (TL) steels as yield strength is increased from 180 to 210 ksi. This feature is called the "strength transition," which is indexed by both the energy scale and fracture appearance.

3. The use of steels in the 180- to 210-ksi yield strength range requires careful consideration of the tradeoffs in fracture resistance for yield strength or metal quality. The Ratio Analysis Diagram provides a simple analytical procedure for the engineering interpretation of these factors.

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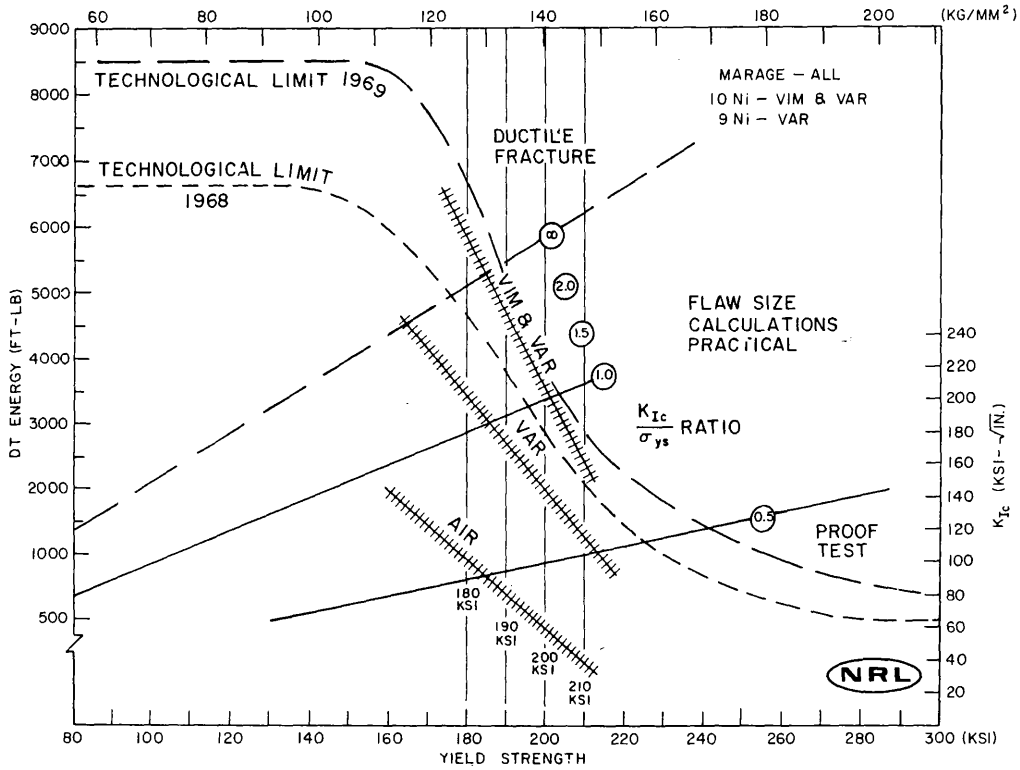

Fig. 10 - Illustrating the 1969 Technological Limit line for ultrahigh strength steels and the influence of melting practice on the structural performance as interpreted by the use of the Ratio Analysis Diagram

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Appendix A

PRODUCTION EXPERIENCE, MELTING PRACTICES, AND COMPOSITIONS OF 18Ni, 12Ni, 9Ni, AND 10Ni ULTRAHIGH-STRENGTH STEELS

PRODUCTION EXPERIENCE

The 18Ni maraging steels have found applications in many different industries including machine tool, chemical, and tool and die. Production has steadily increased for the past several years, and it is now approximately 500 to 600 tons per year. An ASTM standard specification has been issued to cover procurement of three grades of the 18Ni maraging steels (A1).

The 12Ni maraging steel composition was developed to provide a lower strength, lower alloy-content steel with concomitant higher fracture toughness values than those developed by the early versions of the 18Ni maraging steels. To date, however, there has been no commercial application of this material, and consequently, no standard specification has been written for the 12Ni maraging steels. Production and evaluation of the 12Ni maraging steels have been limited to plates produced from twelve small (1/2-, 1-, and 1-1/2-ton) heats and four pilot production (10- to 15-ton) heats.

The 9Ni Q&T steel with 0.20%C is the most recent (late 1966) addition to the family of other 9Ni steels containing higher (0.25 to 0.45 percent) C contents, which have been commercially available since 1962. The basic modification in C content was made to improve weldability, and increased amounts (to nominally 1 percent) of secondary hardening elements such as Cr and Mo have been added for improvement of tempering response. The 9Ni steels have been produced with a single VAR process, providing carbon deoxidation of unkilled electrode material which had been air melted in a basic electric furnace (EF).

To date, commercial production of the 9Ni alloy has been limited to VAR ingots produced from three EF (70-ton) heats. Usually ten or more electrode ingots are poured from each air-melted EF heat. Although production of the 9Ni steel with 0.20%C has been limited, a large background of experience in VAR-C deoxidation melting practice exists for the production of a larger tonnage of the earlier, higher C content 9Ni steels which have found industrial applications. To date, the 9Ni steel with 0.20%C has been used only in applications involving sheet-metal thicknesses, and tentative specifications have been drafted for this material (A2).

The 10Ni steel is the most recently developed alloy for the 180- to 210-ksi yield strength range. This alloy was evolved on the basis of results obtained with 1/2-in. plates rolled from small (350-lb) VIM heats of various 9- to 12%Ni steel compositions in which other elements (C, Mn, Cr, Mo, Co, etc.) were statistically varied to determine their effects on properties. Simultaneous plate- and weld-metal development programs resulted in similar approximate compositions of high Ni, high Co, and low Cr and Mo contents and a minimum amount (0.10 to 0.12 percent) of carbon as the optimum composition. The secondary hardening elements (Cr and Mo) were found to be required in the high Ni, high Co content steel to attain the yield strength level greater than 180 ksi.

Semipilot production of the 10Ni steel has been limited to four 15-ton VIM heats, all of which were poured into electrode ingot forms. Except for one 5-ton electrode ingot

from the first VIM heat, all other electrodes were subsequently VAR processed. NRL investigations of the 10Ni steel have involved only double vacuum (VIM and VAR) processed plate material from the first two 15-ton VIM heats. The 10Ni steel is still in the experimental development stage, and a standard specification is not available.

MELTING PRACTICES

The 9Ni and 10Ni steels have been produced exclusively by special vacuum melting practices. The 18Ni and 12Ni steels, on the other hand, have been produced by four melting practices ranging from conventional air melting to the special vacuum melting practices employed for the 9Ni and 10Ni steels. These highly alloyed materials do not undergo a transition in microfracture mode from cleavage to ductile (microvoid coalescence) in the ambient temperature range, as do conventional and some low-alloy steels. Fracture occurs by microvoid coalescence through the strength transition region for both the flat, fibrous fracture regions as well as the slant, shear regions. Since nonductile particles act as nuclei for premature voids, cleanliness has a great effect on the fracture process on a micro scale and on fracture toughness on a macro scale. Melting practices which decrease the number and size of brittle particles will therefore greatly influence the levels of fracture resistance attained by these ultrahigh-strength metals.

When VAR processing is used, the initial EF melting is performed without the use of strong deoxidizers, and the resulting electrode ingot product is relatively high in oxygen content in the form of oxides. In subsequent vacuum-arc remelting at low pressures, C acts as a deoxidizer capable of reducing oxygen content to very low levels, provided the oxygen is not "fixed" as highly stable oxides. During vacuum-arc remelting, a carbon "boil" results from the evolution of CO gas. The VAR practices are aimed at producing material free of solid deoxidation products as inclusions, and a lower residual gas (O, H, and N) content than that produced by conventional air melting practices.

The VIM process is capable of producing cleaner steel with a lower residual gas content than that of any other single melting process because the molten metal is held and stirred under reduced pressure for a longer period of time. The VIM process generally employs a furnace charge of a special, low S-content, EF iron. The desired chemical composition is controlled more closely with the VIM process, since all alloy additions are made under vacuum with C controlling the oxygen content. This permits accurate additions of the easily oxidized elements like Al, Ti, Zr, and B for alloying purposes. Since these elements and Si and Mn are not active as deoxidizers, the resultant product contains a minimum of inclusions. Vacuum-arc remelting of a VIM heat can result in metal with a slightly lower residual gas and possibly a lower C content.

CHEMICAL COMPOSITION

Table A1 presents chemical compositions of several 180- to 210-ksi yield-strength steels melted under various conditions. It is apparent that increasing the sophistication of the melting practice generally lowers the level of residual (impurity) elements. The optimum chemical compositions of these 180- to 210-ksi yield strength steels are obtained from a combination of air melting and vacuum melting practices.

Unfortunately, S and P are not removed by vacuum melting processes because these elements have a low vapor pressure and are strongly associated with iron in the molten condition. They must be removed through chemical reaction, and this is accomplished by means of basic slags. The use of double or multiple slagging operations is effective in attaining "low" levels of S and P. P is removed by oxidation to P_2O_5 which rises into the slag where it forms a calcium phosphate compound. S is removed under reducing

Table A1
Chemical Compositions of Several 18Ni, 12Ni, 9Ni, and 10Ni Steels for Various Melt Practices

NRL No.	Melt Practice	Steel Type	Composition (wt-%)										
			Ni	Co	Cr	Mo	Ti	Al	Mn	Si	P	S	C
D63	AIR	18Ni	18.3	7.4	ND	5.30	0.24	0.12	0.03	0.08	0.001	0.004	0.040
F59	AIR	18Ni	18.2	8.7	ND	3.25	0.16	0.10	0.02	0.01	0.005	0.010	0.007
G19	AIR	18Ni	18.0	8.1	ND	2.72	0.12	0.14	0.04	0.02	0.003	0.008	0.019
H84	AIR	12Ni	12.1	ND	3.87	3.05	ND	ND	0.10	0.12	0.007	0.010	0.029
G35	AIR	12Ni	11.8	ND	5.28	3.35	0.12	0.12	0.10	0.10	0.004	0.004	0.027
J66	AIR	12Ni	12.3	ND	4.71	3.65	0.21	0.16	0.08	0.07	0.007	0.005	0.033
F56	VAR	18Ni	18.0	8.7	ND	3.38	0.18	0.09	0.03	0.01	0.004	0.018	0.015
F84	VAR	18Ni	17.4	7.7	ND	5.20	0.32	0.10	0.05	0.13	0.005	0.007	0.025
G77	VAR	18Ni	17.4	9.1	ND	4.85	0.68	0.23	0.04	0.12	0.005	0.002	0.020
F55	VAR	12Ni	12.0	ND	4.91	3.15	0.18	0.21	0.03	0.09	0.004	0.010	0.015
J71	VAR	12Ni	12.5	ND	4.81	3.55	0.20	0.18	0.08	0.08	0.007	0.004	0.029
J72	VAR	12Ni	12.5	ND	4.81	3.65	0.20	0.18	0.08	0.10	0.007	0.005	0.029
L68	VAR	9Ni	8.9	4.5	0.91	0.92	ND	ND	0.10	0.005	0.006	0.003	0.20
L70	VAR	9Ni	8.9	4.5	0.79	0.92	ND	ND	0.11	0.015	0.004	0.003	0.19
G66	VIM	18Ni	17.8	8.1	ND	2.35	0.20	0.15	<.01	0.01	0.005	0.003	0.020
K48	VIM	18Ni	18.0	7.8	ND	3.03	0.17	ND	0.02	0.006	0.002	0.006	0.001
J5	VIM	12Ni	12.1	ND	4.83	3.10	0.24	0.21	0.03	0.06	0.003	0.007	0.003
J8	VIM	12Ni	11.8	ND	5.16	3.30	0.24	0.13	0.04	0.05	0.005	0.007	0.005
K14	VIM & VAR	18Ni	18.5	8.50	ND	3.34	0.20	0.07	0.03	0.02	0.005	0.008	0.005
L26	VIM & VAR	12Ni	11.8	ND	5.30	2.98	0.18	0.40	0.09	0.05	0.005	0.005	0.010
L52	VIM & VAR	10Ni	9.4	8.0	2.2	0.94	ND	ND	0.07	0.04	0.003	0.002	0.12
L90	VIM & VAR	10Ni	9.4	8.1	2.2	0.92	ND	ND	0.03	0.07	0.006	0.003	0.11

ND = Not determined

conditions by direct absorption into the basic slag and also through the formation of MnS which rises into the slag. The control of these chemical reactions and the oxidation of other elements in the metal bath and slag is a complex operation, and no attempt is made here to provide a definitive treatise on steelmaking practice. It is sufficient to note that there is essentially no loss of major alloy elements (Ni, Cr, Mo, Co, Al, Ti) in the various commercial vacuum melting processes.

The effects of S content on fracture toughness properties have been demonstrated by several investigators for several different steels (A3-A5). In these studies, S content was varied from 0.003 to 0.179 percent. No marked effect on transition temperatures with increasing S content has been observed, but a very dramatic effect on the upper shelf level of fracture toughness occurs with only small amounts of S present. For example, using low-residual-element, VIM laboratory heats of a 12Ni (180-ksi yield strength) maraging steel, Porter and others showed that a 100 percent increase in the Charpy-V-notch energy-shelf values could be obtained by lowering the S content from 0.010 percent to below 0.005 percent (A5).

Investigation of the effects of C content on shelf-level toughness of several Q&T steels (A6,A7) have shown a deleterious effect on toughness with increasing C content similar to that described above for the effects of S. For Q&T steels, the optimum C content is approximately the minimum amount necessary to achieve the desired yield strength. Although required for strengthening of the conventional Q&T steels, C is a residual (impurity) element in the maraging steels which are sometimes described as "carbon-free" steels. The data of Table A1 imply that a potent improvement in toughness

can be expected in the 18Ni and 12Ni maraging steels as C content is reduced from the maximum specified value (0.03 percent) to less than 0.01 percent.

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Appendix B

TENSILE CHARACTERISTICS OF 180- TO 210-KSI YIELD-STRENGTH STEELS AS INFLUENCED BY HEAT TREATMENT

Both the 18Ni and 12Ni maraging steels represent age-hardening alloy systems. Properties are developed by a solution annealing (austenitizing) heat treatment, followed by aging heat treatments. Comparatively low hardness and strength values are developed by maraging steels in the as-quenched condition (air or water cooled from the austenitizing temperature). For example, nominal values for all grades of 18Ni steels in the as-quenched condition are 145 ksi tensile strength, 115 ksi yield strength and 29 Rockwell C hardness. During the aging heat treatment, the maraging steels are strengthened (increased tensile strength, yield strength, and hardness) by precipitation of complex metallic particles in an essentially "carbon-free" Fe-Ni martensite matrix. The kinetics and mechanisms involved in strengthening the maraging steels have been summarized in several review articles (B1-B4), and the various phase transformations and age-hardening reactions that occur in different maraging steel alloys have been reported in detail by Floreen (B5). Depending on composition, annealing temperature, and aging time and temperature, the 18Ni marage steels can be strengthened to yield strength levels ranging from approximately 180 ksi to 300 ksi, and the 12Ni marage steels to yield strength levels ranging from 150 to 215 ksi.

In the as-quenched condition, both 10Ni and 9Ni steels are fully hardened and develop maximum tensile strength values commensurate with their respective C contents. Typical engineering load-strain diagrams obtained for the 10Ni and 9Ni steels are shown in Fig. B1. Significant reductions in tensile strength values occur when these steels are tempered for the temperatures and times shown in Fig. B1, center and right. The 0.2-percent offset yield strength values are approximately 150 ksi for both steels in the as-quenched condition, and the yield strength is increased to approximately 180 ksi for the mill Q&T condition, Fig. B1 center. Yield strength can be reduced below 180 ksi by prolonged tempering times as shown in Fig. B1 right. The strengthening mechanisms with these steels have not been fully investigated, but the data given in Fig. B1 suggest that both the 10Ni and 9Ni steels are similar to conventional Q&T alloy systems. These systems use C as the primary hardening element with enhanced temper resistance due to the secondary hardening elements (Cr and Mo) for tempering in the range of 900° to 1050°F.

The proportional limit stress is frequently required in design calculations. The data given in Fig. B1, center and right, indicate that the proportional limit stress is nearly stable for both steels, in contrast to significant reductions in tensile strength values for prolonged tempering treatments. For the as-quenched condition, however, extremely low proportional limit stresses are developed by both steels as noted in Fig. B1, left. This can be important if these materials are improperly welded, and heat-affected-zone (HAZ) areas of untempered material are formed that have tensile characteristics shown for as-quenched material. The well-known tempering-bead welding technique should be mandatory for the final weld crown passes to preclude the development of untempered HAZ material at the toe region of the weld crown.

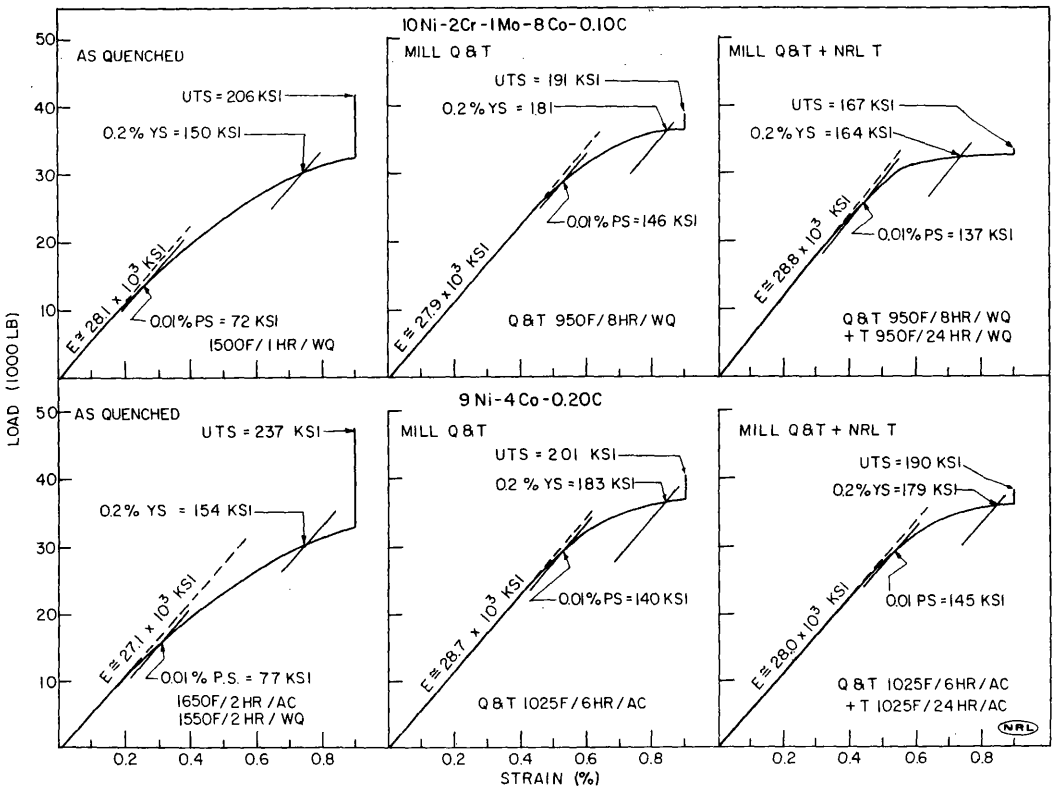

Fig. B1 - Typical engineering load–strain diagrams for 10Ni (top) and 9Ni (bottom) steels developed for various heat-treatment conditions as noted

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Appendix C

Summary data of melt practice, heat-treatment conditions, tensile properties, and Dynamic Tear energy for 18Ni, 12Ni, 9Ni, and 10Ni high-strength steels are presented in Tables C1 through C10.

Table C1
Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for Air-Melted, 18Ni Maraging Steels

NRL No.	Heat Size (tons)	Nominal % Ni-Co-Mo	Austenitized °F/hr/*	Aged °F/hr/*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
					0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
D63A	10	18-7-5	1500/1/AC	900/3/AC	229.5	240.3	9.0	45.9	<500
D63B	10	18-7-5	1750/1/AC	900/3/AC	234.5	245.7	7.0	29.2	<500
F59	1	18-9-3	1500/1/AC	900/3/AC	201.3	208.9	12.0	57.6	1234
G19A	80	18-8-3	1700/1/WQ	850/2/AC	159.5	173.1	14.0	54.2	2020
G19B	80	18-8-3	1700/1/WQ	850/5/AC	173.6	185.2	13.0	53.7	1460
G19C	80	18-8-3	1700/1/WQ	900/7/AC	186.4	194.4	11.5	47.8	845
G36A	80	18-8-3	1500/1/WQ	900/1/AC	167.4	176.6	14.3	56.5	1145
G36B	80	18-8-3	1500/1/WQ	900/3/AC	179.0	187.6	13.0	53.6	1010
G36C	80	18-8-3	1500/1/WQ	900/7/AC	192.7	200.0	12.0	50.5	700

*AC = Air cooled
WQ = Water quenched

Table C2
Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for Vacuum-Arc-Remelted (VAR) 18Ni Maraging Steels

NRL No.	Heat Size (tons)	Nominal % Ni-Co-Mo	Austenitized °F/hr/*	Aged °F/hr/*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
					0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
F56	1	18-9-3	1500/1/AC	900/3/AC	204.2	212.2	12.0	59.8	1410
F57	1	18-9-5	1500/1/AC	900/3/AC	279.7	293.6	8.5	42.5	<500
F69	0.5	18-8-2	1500/1/AC	900/3/AC	155.5	163.5	15.3	67.4	4370
F84	0.5	17-8-5	1500/1/AC	900/3/AC	259.6	266.1	9.5	49.0	<500
G56 (A)	15	18-8-5	1500/1/AC	900/1/AC	223.0	234.1	10.5	45.1	670
G56 (B)	15	18-8-5	1500/1/AC	900/3/AC	263.0	271.8	9.0	40.8	520
G56 (C)	15	18-8-5	1500/1/AC	900/7/AC	266.8	277.4	6.0	25.9	475
G57 (A)	15	18-8-5	1500/1/AC	900/1/AC	185.6	193.8	13.8	60.9	2150
G57 (B)	15	18-8-5	1500/1/AC	900/3/AC	217.5	224.4	12.0	56.6	810
G57 (C)	15	18-8-5	1500/1/AC	900/7/AC	226.6	233.3	11.8	55.9	780
G77 (A)	15	18-9-5	1500/1/AC	900/1/AC	247.2	258.5	8.5	35.0	530
G77 (B)	15	18-9-5	1500/1/AC	900/3/AC	284.0	297.1	5.5	27.7	400
G77 (C)	15	18-9-5	1500/1/AC	900/7/AC	296.5	303.3	5.7	24.2	460

*AC = Air cooled
WQ = Water quenched

Table C3
Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for Vacuum-Induction-Melted (VIM) 18Ni Maraging Steels

NRL No.	Heat Size (tons)	Nominal Ni-Co-Mo	Austenitized °F/hr/*	Aged °F/hr/*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
					0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
G66	1	18-8-2	1500/1/AC	900/3/AC	192.4	197.5	13.8	61.4	3315
G67	1	18-8-2	1500/1/AC	900/3/AC	190.3	197.2	13.3	58.0	3990
K48	15	18-8-3	1500/1/WQ	900/3/AC	183.1	188.3	13.6	62.9	3925
K49 (K48)	15	18-8-3	1500/1/WQ	900/30/AC	187.9	194.4	14.3	60.4	2830
K50 (K48)	15	18-8-3	1500/1/WQ	900/16/AC	190.1	195.9	13.0	61.2	2795
K51	15	18-8-5	1650/1/WQ 1525/1/WQ	900/1/AC	221.4	231.9	11.0	47.6	1175
K52 (K51)	15	18-8-5	1650/1/WQ 1525/1/WQ	900/8/AC	260.1	269.5	7.1	34.7	845
K57 (K51)	15	18-8-5	1650/1/WQ 1525/1/WQ	900/5/AC	259.7	266.2	9.5	44.4	810
K67 (K48)	15	18-8-3	1700/1/WQ 1400/1/WQ	900/3/AC	189.2	191.6	13.5	62.7	2965
K74 (K51)	15	18-8-5	1650/1/WQ 1525/1/WQ	900/3/AC	249.1	257.2	10.0	47.3	1055

*AC = Air cooled
WQ = Water quenched

Table C4

Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for Vacuum-Induction-Melted and Vacuum-Arc-Remelted (VIM & VAR) 18Ni Maraging Steels

NRL No.	Heat Size (tons)	Nominal Ni-Co-Mo	Austenitized °F/hr/*	Aged °F/hr/*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
					0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
J16 (A)	15	18-8-5	1650/1/AC	900/3/WQ	259.5	262.7	8.5	43.5	760
J16 (B)	15	18-8-5	1650/1/AC	900/3/AC	248.1	258.2	10.0	43.7	850
K14 (M29)	15	18-8-3	1650/1/WQ	900/3/AC	193.1	201.4	12.5	59.5	3170
K14 (M30)	15	18-8-3	1650/1/WQ	900/8/AC	197.5	210.3	12.0	57.9	2590
K14 (M30A)	15	18-8-3	1650/1/WQ	900/24/AC	210.7	218.0	12.0	56.5	1915
K14 (M31)	15	18-8-3	1650/1/WQ	900/3/AC	191.3	200.2	12.5	58.9	3340
K14 (M28)	15	18-8-3	1650/1/WQ	900/8/AC	199.5	207.7	12.5	59.8	2725
K14 (M28A)	15	18-8-3	1650/1/WQ	900/24/AC	211.1	218.3	12.2	56.7	1663
K15 (A)	15	18-8-3	1650/1/WQ	900/3/AC	204.9	212.2	13.0	57.0	2780
K15 (B)	15	18-8-3	1650/1/WQ	900/3/AC	191.6	201.3	13.0	59.4	3300
K16 (K13)	15	18-8-3	1650/1/WQ	900/24/AC	213.3	211.2	12.0	56.2	2480
K17 (K15)	15	18-8-3	1650/1/WQ	900/1/AC	172.1	183.3	14.7	61.7	4480

*AC = Air cooled
WQ = Water quenched

Table C5
Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for Air-Melted 12Ni Maraging Steels

NRL No.	Heat Size (tons)	Austenitized °F/hr/*	Aged °F/hr/*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
				0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
G35A	20	1500/1/AC	900/1/AC	183.1	189.1	14.0	57.0	1740
G35B	20	1500/1/AC	900/3/AC	184.8	190.4	13.5	54.5	1935
G35C	20	1500/1/AC	900/7/AC	187.9	193.5	13.0	55.2	1430
H84	15	1500/1/WQ	900/3/AC	177.7	183.4	14.3	53.7	1280
H95	1	1600/1/AC	900/3/AC	173.5	183.8	14.0	58.8	2795
J66A	7.5	1500/1/AC	900/3/AC	185.3	188.0	13.8	56.7	1520
J66B	7.5	1700/2/AC 1400/2/AC	900/3/AC	176.3	179.9	13.5	52.1	2515
J67A	7.5	1500/1/AC	900/3/AC	178.6	182.3	15.0	57.2	1375
J67B	7.5	1700/2/AC 1400/2/AC	900/3/AC	178.0	181.9	14.0	54.9	2660

*AC = Air cooled
WQ = Water quenched

Table C6
Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for Vacuum-Arc-Remelted (VAR) 12Ni Maraging Steels

NRL No.	Heat Size (tons)	Austenitized °F/hr/*	Aged °F/hr/*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
				0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
F55	1	1900/1/AC	900/3/AC	162.5	174.8	14.3	60.0	4090
F83	0.5	1500/1/AC	900/3/AC	154.4	156.2	18.0	67.3	5750
J71A	7.5	1500/1/AC	900/3/AC	176.8	183.2	14.5	59.6	4425
J71B	7.5	1700/1/AC 1400/1/AC	900/3/AC	174.9	179.2	15.0	64.1	5095
J72A	7.5	1700/1/WQ 1400/1/WQ	900/3/AC	177.1	180.2	16.0	63.4	4145
J72B	7.5	1500/1/AC	900/3/AC	177.3	183.3	14.5	59.2	3530
J72C	7.5	1700/2/AC 1400/2/AC	900/3/AC	179.2	183.5	15.2	61.0	3660

*AC = Air cooled
WQ = Water quenched

Table C7
Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for Vacuum-Induction-Melted (VIM) 12Ni Maraging Steels

NRL No.	Heat Size (tons)	Austenitized °F/hr/*	Aged °F/hr/*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
				0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
J5	15	1500/1/AC	900/20/AC	176.2	185.3	13.5	58.3	4260
J6 (J5)	15	1500/1/AC	900/20/AC	184.4	190.0	13.5	55.7	3570
J6 (J64) (J5)	15	1500/1/AC	900/20/AC 850/24/AC	193.3	198.4	13.5	57.9	3500
J6 (J65) (J5)	15	1500/1/AC	900/20/AC 825/24/AC	192.6	198.0	13.0	56.8	3260
J7 (J5)	15	1500/1/AC	900/20/AC	181.5	188.5	14.5	62.3	4515
J8 (J5)	15	1500/1/AC	900/2/AC	162.6	170.6	15.8	64.1	5255
J8 (J63) (J5)	15	1500/1/AC	900/2/AC 900/3/AC	172.2	178.5	14.8	62.7	5590
J9 (J5)	15	1500/1/AC	900/2/AC	162.5	170.9	16.0	64.5	5360
J9 (M20) (J5)	15	1500/1/AC	900/2/AC 900/3/AC	175.0	182.7	15.0	65.0	5370
J10 (J5)	15	1500/1/AC	900/2/AC	167.3	173.3	15.0	64.1	5180
K22	15	1500/1/WQ	900/24/AC	185.4	189.7	14.7	61.2	4200
K23 (K22)	15	1700/1/WQ 1400/1/WQ	900/24/AC	190.1	195.1	15.7	60.5	3755
K33 (K22)	15	1700/1/WQ 1400/1/WQ	900/3/AC	166.5	174.3	16.5	64.3	4830
J8 (J60)	15	1500/1/AC	900/2/AC 900/19/AC	184.4	190.6	15.5	62.0	4060

AC = Air cooled
WQ = Water quenched

Table C8
Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for Double Vacuum-Melted (VAR AND VIM) 12Ni Maraging Steels

NRL No.	Heat Size (tons)	Austenitized °F/hr/*	Aged °F/hr/*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
				0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
L26	10	1650/1/AC	900/3/AC	172.1	183.2	15.2	64.2	3970
L26	10	1650/1/AC	900/8/AC	179.5	189.0	14.5	65.6	4830
L26	10	1650/1/AC	900/24/AC	192.4	199.4	15.0	63.3	4340

*AC = Air cooled
WQ = Water quenched

Table C9
Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for 9Ni-4Co-0.20C Quenched and Tempered Steels

NRL No.	Melt	Heat Size (tons)	Austenitized °F/hr/*	Tempered °F/hr/*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
					0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
K28	VAR	10	1650/1/AC 1500/1/WQ	1000/2+2/AC	181.3	194.5	15.2	61.3	3968
K29	VAR	10	1650/1/AC 1500/1/WQ	1000/2+2/AC	182.6	200.0	18.0	67.9	4087
K40	VAR	10	1650/1/AC 1500/1/WQ	1000/2+2/AC	178.9	200.4	17.5	66.7	4145
L68	VAR	10	1650/2/AC 1550/2/WQ	None	153.1	237.7	15.8	61.8	1915
L68	VAR	10	1650/2/AC 1550/2/WQ	1025/6/AC	182.9	201.5	18.0	66.0	3436
L68A	VAR	10	1650/2/AC 1550/2/WQ	1025/6/AC 1025/24/AC	179.1	190.6	18.6	68.2	4303
L68B	VAR	10	1650/2/AC 1550/2/WQ	1025/6/AC 950/24/AC	184.0	199.5	17.5	64.7	3055
L70	VAR	10	1650/2/AC 1550/2/WQ	1025/6/AC	185.6	196.5	16.7	64.4	2987

*AC = Air cooled
WQ = Water quenched

Table C10
Summary of Heat-Treatment Conditions, Tensile Properties, and Dynamic-Tear Energy for VIM & VAR 10Ni-8Co-2Cr-1Mo Quenched and Tempered Steels

NRL No.	Heat Size (tons)	Austenitized °F/hr*	Tempered °F/hr*	0.505-in.-Diam. Tensile Test Data				DT at 30°F
				0.2% YS (ksi)	UTS (ksi)	El (%)	RA (%)	
L-52A	15	1500/1	None	148.0	210.7	16.0	60.1	3723
L-52B	15	1500/1	950/7	193.3	208.0	16.5	69.5	4028
L-52C	15	1500/1	950/7 950/7	183.0	190.0	18.0	67.5	5287
L-52D	15	1500/1	900/7	188.1	210.4	16.5	64.2	3785
L-52E	15	1700/1 1400/1	900/3	190.7	215.3	16.7	62.6	3002
L-52F	15	1700/1 1400/1	900/7	191.7	211.8	16.5	64.1	2726
L-90A	15	1500/1	None	150.6	206.1	17.2	66.5	5510
L-90B	15	1500/1	950/8	180.7	196.3	18.0	70.6	5652
L-90C	15	1500/1	950/8 950/5	177.4	184.1	18.0	72.4	6882
L-90D	15	1500/1	950/8 950/24	164.0	166.9	20.0	73.0	7759
L-89E	15	1500/1	950/8	183.1	194.8	17.7	70.4	
L-89F	15	1500/1	950/8 950/7					6800
L-91 (2")	15	1500/2	950/10	179.9	189.7	18.5	72.5	7150 (1" DT)

*Water quenched

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13. ABSTRACT

The yield strength range for steels from 180 to 210 ksi is currently covered by four weldable alloys of the following nominal chemical analysis: 18%Ni-8%Co-3%Mo maraging steel, 12%Ni-5%Cr-3%Mo maraging steel, 9%Ni-4%Co-0.20%C quenched and tempered (Q&T) steel, and 10%Ni-8%Co-2%Cr-1%Mo-0.10%C Q&T steel. Broad ranges of fracture resistance have been reported for these materials based on various fracture tests, and this report presents information for material selection and design guidance by providing an analysis of the interactions between the metallurgical and mechanical parameters that contribute to the fracture resistance of plate products. Definitions of the interaction between the metallurgical and the mechanical aspects are developed with the use of the Dynamic Tear (DT) test and the Ratio Analysis Diagram (RAD), where a close correlation between K_{Ic} values and DT energy values is extended to include materials of high fracture toughness. Limited use was made of the Charpy-V-notch test after it was shown to be unreliable for fine definitions of fracture toughness for these ultrahigh-strength steels. Materials produced from alloys melted under atmospheric air and by various vacuum melting practices were included; metallurgical factors investigated, in addition to melting practice, were rolling procedure and heat treatment.

(Continues)

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Steels in the yield strength range from 180 to 210 ksi are at the midpoint of the "strength transition," which starts from a potentially high level of fracture resistance and drops to a low level of fracture resistance. The dramatic falloff in fracture toughness is also evidenced by the fracture appearance in the 1-in. DT specimens which changes from large, plastic, enclave-type fracture for the best steel at 180 ksi yield strength to a mixed-mode type fracture for the best steel at 210-ksi yield strength. Chemical composition has a direct effect on yield strength, but other factors, mainly purity of the metal, control fracture resistance. All air-melted materials in the 180- to 210-ksi yield strength range are brittle (plane strain properties) in sections exceeding 1 in. in thickness. Vacuum melting significantly improves fracture resistance, and the order for increasing effectiveness is single vacuum-arc remelting, vacuum-induction melting, and double vacuum melting. By optimizing metal processing procedures, material at 180 ksi yield strength can resist fracture initiation at all elastic stress levels in thick sections as long as hardenability limits are not exceeded, while material at 210 ksi yield strength can resist plane strain fractures only in sections of approximately 2 in. even in the absence of metallurgical gradients from the surface to the midthickness position.