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ADVANCED METAL ALLOYS FOR ENERGY NEEDS

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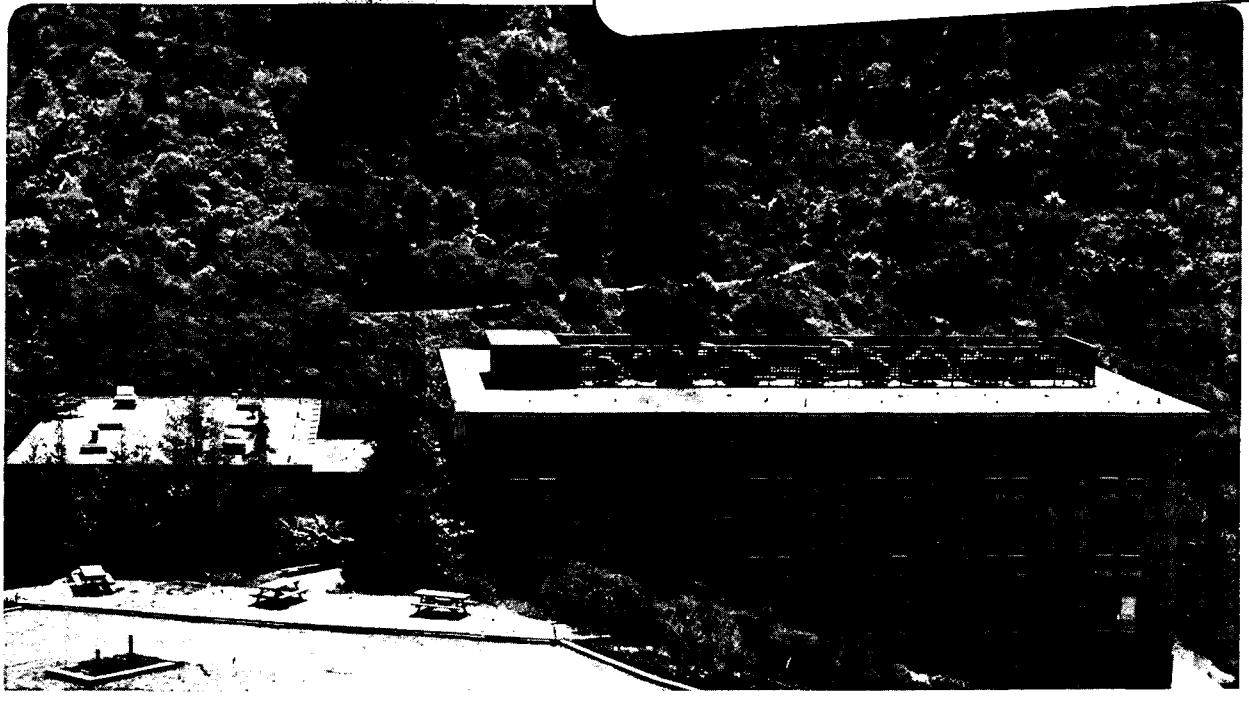

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Advanced Metal Alloys for Energy Needs

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ABSTRACT

Advanced energy technologies create a range of needs for new metal alloys that have exceptional properties that are specifically tailored to the engineering needs of particular systems. To meet these needs in a timely and economical way it has been necessary for the metallurgical community to develop and adopt techniques for systematic alloy design. Those techniques are described and illustrated with three specific examples: (1) the development of new cryogenic structural steels for the case and support structure of high field superconducting magnets; (2) the development of Al-Li alloys for fuel savings in aircraft; (3) the development of formable sheet steels for use in the automotive industry.

INTRODUCTION

Recent developments in energy technology have created a variety of needs for new metal alloys, many of which are documented in the papers presented in this conference. Advanced methods of energy production, including nuclear fission, fusion, and fossil energy systems, require structural alloys that will perform well at extreme temperatures, under high loads, or in reactive environments. Modern approaches to energy conservation in transportation and communication require metal alloys that are tailored for the specific needs of particular devices. The alloys that satisfy each of these needs are required to be low in cost, energy efficient in production and manufacture, and conservative in their use of critical and strategic materials.

It is widely recognized that this nation is handicapped in its response to the need for advanced metal alloys. Its problems derive from the relative maturity of the field and the ongoing contraction of the basic metals industry. It is a simple fact that the obvious metal alloys have already been tried and tested, and have found their appropriate places in engineering technology. The search for new alloys that offer substantial property improvements is an increasingly difficult one. But because of the contraction of the basic metals industry, the level of effort devoted to alloy development has been declining for almost two decades.

Yet despite the problems of the industry, metal alloy development is an active and exciting field that is generating important new materials for advanced energy needs. While the level of effort may have declined the sophistication of the effort has increased dramatically. This increased sophistication is a consequence of advances in the science of alloy behavior, coupled with the development of high resolution tools for alloy characterization and analysis. It has long been possible for chemists to manipulate the structure of molecules to control their properties and for specialists in semiconductors to fine-tune electrical properties. But because of the microstructural complexity of metal alloys, the uncertainty in their structure-property relations, and the usual need to process them in bulk form, it has been difficult to progress beyond the trial-and-error method in structural alloy development. That situation is rapidly changing. An increasing fraction of the new alloys that are offered for use are designed rather than discovered, and have microstructures that are tailored to achieve pre-selected combinations of engineering properties.

The present paper is intended both to describe some of the new alloys that may impact energy technology and to discuss the emerging science of alloy design that has helped to make those alloys possible. For brevity three examples have been selected from a very long list of candidate alloys, many of which are described elsewhere in the conference. The examples that will be treated are: (1) new structural alloys for high field superconducting magnets, a development that appears to be essential to the realization of magnetic fusion energy and requires the creation of alloys having outstanding strength-toughness combinations at extreme cryogenic temperatures; (2) aluminum-lithium alloys for aircraft structures, a development that offers substantial short-term fuel savings in aircraft and involves the creation of alloys that combine

strength, toughness, fatigue and corrosion resistance, low density and high modulus; (3) new formable steels for manufacturing, a development that can improve the efficiency of manufacturing processes and products, and involves the design of inexpensive sheet alloys that are capable of large, stable plastic deformation.

METHODS OF ALLOY DESIGN

Virtually the whole content of materials science can be phrased in two statements: (1) the properties of a material are determined by its composition and its microstructure, i.e., by the chemical species it contains and the manner in which those chemical species are organized into distinct phases, grains, and defects; (2) the microstructure of a material is determined by its composition and the processing it has received. An engineer who is possessed of all knowledge would hence design a new alloy in two steps. Given a set of target properties, he would identify a combination of composition and microstructure that would achieve them. Then, knowing the proper composition, he would select a processing sequence to create the appropriate microstructure.

In the real world of engineering metallurgy it is rarely possible to follow this idealized recipe, since both the structure-property and the structure-processing relations are imperfectly known. The design of a new alloy is usually preceded by a period of enlightened Edisonian testing and failure analysis to reduce the problem to manageable size. The metallurgist begins by selecting an existing alloy that most closely matches the target properties, and uses a combination of probative testing and microstructural analysis to identify the chemical or microstructural flaws that prevent the alloy from reaching those properties. He then changes composition and processing in an attempt to eliminate the microstructural flaw, tests the modified alloy, and iterates the procedure until a successful result is obtained.

The probability of success in an alloy design effort depends on how well the structure-property and structure-processing relations are known. Given the results of basic metallurgical research over the last several decades, the microstructural mechanisms of yielding and fracture, for example, are reasonably well understood. This understanding is reflected in the recent appearance of a number of promising new alloys that have excellent combinations of strength and toughness. Many of the mechanistic phenomena that govern oxidation, corrosion, stress corrosion cracking and hydrogen embrittlement are also understood at a level that permits the systematic development of improved alloys. On the other hand, the elements of microstructure that govern response to large plastic strain, work hardening, and plastic instability are not well understood, impeding the systematic design of alloys that offer exceptional formability or fatigue resistance.

EXAMPLES

A. Structural Alloys for High Field Superconducting Magnets

In magnetic fusion energy devices, nuclear fusion will be accomplished in a plasma confined in a high magnetic field. The magnets that create this field will be superconducting coils to minimize the energy required to operate the device, and will be bathed in liquid helium to maintain the superconducting state at a temperature of 4.2K or below. When such a magnet operates, the Lorentz force due to the coupling between the superconducting current and the magnetic field presses the coil against the magnet case. The magnitude of the resulting stress in the case increases with both the magnetic field strength and the size of the magnet. Since commercial systems will require large, high-field magnets, the structural alloys used for the magnet case and supports must be selected with care. The large research magnets constructed to date have used modified stainless steels or Fe-based superalloys for the cryogenic structure. However, design studies suggest that these alloys may not have the strength and toughness required for commercial devices.

To illustrate the scale of these devices, Figure 1 shows the coil case for one section of the Ying-Yang coil set for the Mirror Fusion Test Facility (MFTF-A) at the Lawrence Livermore National Laboratory, which was designed to operate at a peak magnetic field of 7.68 Tesla [1]. This coil case is a welded construction of 304LN stainless steel (low carbon, nitrogen strengthened), made in plates of up to 5 inch thickness. Figure 2 shows the strength and toughness specifications for the structural alloy along with a band that represents the 4K strength-toughness characteristic of conventional Fe-Ni-Cr stainless steels [2].

Figure 2 also includes the strength-toughness specification for the magnet case of a commercial tokomak device as recently projected by the Japan Atomic Energy Research Institute (JAERI) [3]. These specifications substantially exceed the capability of the conventional stainless steels. While no strictly comparable studies have been published in the United States, informal projections at LLNL suggest that the Japanese numbers are realistic. It follows that new high-strength, high toughness cryogenic structural alloys are needed.

Figure 3 illustrates some of the mechanical property issues that underlie the design of cryogenic structural alloys. At high temperature all candidate alloys have relatively low yield strength, but high fracture toughness. The fracture mode is ductile; the alloys break through the nucleation and coalescence of voids that form predominantly at inclusions in the bulk. The toughness of the alloy in the ductile mode is a decreasing function of yield strength, as illustrated in the diagram at the upper right. As the temperature is lowered the alloy yield strength increases, as illustrated in the 'Yoffee diagram' at the lower left. If the yield strength rises to exceed a critical value that is associated with the onset of brittle fracture the alloy becomes brittle, and its toughness drops precipitously over a narrow temperature range that defines the ductile-brittle transition temperature. To achieve a good combination of strength and toughness at low temperature the ductile-brittle transition must be suppressed so that the alloy fractures in a ductile mode, and the strength-toughness characteristic of the

alloy must be raised so that the alloy retains high toughness at design strength.

Three classes of alloys are now under development to meet the properties defined by the 'JAERI box'. The first of these are improved, high-purity versions of the conventional Fe-Ni-Cr stainless steels. The conventional stainless steels fracture in a ductile mode at 4K, but have relatively low toughness when their strengths are high. Since the ductile fracture in these alloys is governed by voids that nucleate at inclusions the toughness can be improved by reducing the density of inclusions, i.e., by increasing the purity of the alloy. Japanese researchers at the Nippon Steel Corporation have demonstrated the possibility of reaching high strength-toughness combinations in ultra-pure alloys [4]. However, these alloys will be costly, and must be welded to a corresponding purity if the welded case is to have the properties of the alloy plate.

The second promising class of alloys includes the Fe-Mn austenitic steels that are under intensive development in Japan. Austenitic Fe-Mn steels have the advantage that they can accept relatively high nitrogen contents in solid solution. Nitrogen is a potent strengthening solute at low temperature, and, if it is retained in solution, increases strength with a relatively minor sacrifice in toughness. The alloys also have a high work-hardening coefficient. They can be made to have strength-toughness combinations that are superior to those of the Fe-Ni-Cr stainless steels, provided that they are adjusted in composition to stabilize the austenite phase and avoid intergranular fracture at low temperature. The challenge with the Fe-Mn steels has been to strengthen them sufficiently to meet the JAERI target while preserving weldability.

Figure 4 shows 4K strength-toughness data for an 18Mn-16Cr-5Ni-0.22N alloy that was made and tested in a joint program between the Lawrence Berkeley Laboratory and the Kobe Steel Company [5]. The high Cr content was added to make the alloy corrosion-resistant, but necessitates the addition of Ni to prevent the formation of undesirable intermetallic phases. The data document the superior strength-toughness combination of the alloy, particularly in the mechanically-worked condition. When the alloy is tested as hot-rolled at 1200°C it meets the JAERI strength-toughness criteria. Similar results were obtained for a 22Mn alloy made by Kobe Steel using conventional melting practice [6].

Research on the Fe-Mn cryogenic steels is continuing. The 18Mn and 22Mn alloys described above meet target properties, but only if mechanical work is retained in the structure. It is, therefore, unclear whether these alloys can be welded without a serious loss of strength in the weldment and the heat affected zone. The Ni addition is costly and produces undesirable long-lived radioactive species if the alloy is subjected to irradiation in service. The Ni addition can probably be eliminated, along with much of the Cr, by dropping the requirement that the alloy be stainless. These issues are under investigation.

The third interesting class of alloys are the ferritic structural steels. Ferritic cryogenic alloys such as Fe-9Ni are standard structural materials for use at 77K and above. They reach very high strength levels at 4K, but are brittle when given conventional heat treatments.

The source of the embrittlement is illustrated in Figure 5, which is a transmission electron micrograph of a transgranular cleavage crack in an Fe-Ni alloy that was tested below the ductile-brittle transition [7]. The alloy microstructure consists of parallel laths of martensite that are organized into packets of laths of almost identical crystallographic orientation. Because of this crystallographic alignment the laths within a packet tend to cleave as a unit along a common (100) plane. The alloy hence has a large effective grain size and a ductile-brittle transition temperature above 4K.

The Fe-Ni steels are made suitable for structural use at 77K and above by giving them intercritical tempering treatments that have the effect of precipitating islands of the high temperature austenite phase along the boundaries of the martensite laths. While there are subtleties in the behavior of this austenite during fracture, its principal role is to break up the crystallographic alignment of the martensite laths within a packet, which refines the effective grain size of the alloy and increases its resistance to cleavage fracture, as suggested by the plot in the lower right of Figure 3 [7]. However, the austenite islands only partly decompose the packet. Intercritical tempering is not sufficient to suppress the ductile-brittle transition temperature to below 4K.

The metallurgical treatments that have been found promising for toughening ferritic alloys at 4K are thermal cycling treatments, such as the '2B' [8] and '2K' [9] treatments of 12Ni steels, that have the effect of breaking the martensite laths into independent grains of extremely small size. Some of the strength-toughness results achieved with these heat treatments are plotted in Figure 6. The data show that it is possible to treat high strength ferritic alloys so that they have strength-toughness combinations that are superior to those of the conventional stainless steels at 4K. The alloys tested to date do not satisfy the JAERI specifications, but also are not completely ductile at 4K. There is good reason to believe that further improvements in the grain refinement treatment will yield significant further increases in 4K toughness.

One particular advantage of the ferritic cryogenic steels is their apparent weldability [10]. The best thermal cycle for the grain refinement of these alloys is a rapid heat-and-quench cycle that reverts the alloy to austenite and re-transforms it to lath martensite again. If the alloy is welded with a multipass welding procedure in which each successive weld bead reheats the material that was previously deposited then the weld metal and heat affected zone are given multiple rapid thermal cycles and reach an extremely fine grain size. The result is that the ferritic Fe-Ni steels can be welded so that they retain high toughness at cryogenic temperature.

There is active research on each of the three alloy classes described above. Given that the alloy development effort is not complete and that the design of a commercial fusion reactor is not settled, it is not clear which of these alloys, or which other alloys, will be used in particular components of the magnet system. But there is good reason to believe that suitable cryogenic structural alloys can be made available.

B. Aluminum-Lithium Alloys for Aerospace Structures

Since both the fuel efficiency and the performance of an aircraft are strongly influenced by its weight, the aerospace industry is continually in need of light-weight structural materials that have the mechanical properties needed for reliability in service. Modern aircraft structures are primarily aluminum alloy. Glass- and graphite-epoxy composite materials are being used increasingly in non-critical structural components because of their exceptionally high modulus and low density. Composite materials will inevitably be used more extensively in future aircraft, but their high cost, orthotropic mechanical properties and poor damage tolerance are continuing problems. It is, moreover, extremely difficult to incorporate composite materials into existing aircraft designs.

These considerations suggest the need for new aerospace alloys that occupy the intermediate ground between the high strength aluminum alloys and the advanced composites, achieving the strength, toughness, damage tolerance, and formability of current aerospace aluminum alloys at lower density and higher modulus. Such alloys could be incorporated into existing designs and even retrofitted onto existing aircraft to achieve immediate weight and fuel savings, and would provide an attractive alternative material for critical structural components in future systems. Such alloys are being developed, based on the Al-Li alloy system. The initial commercial grades should be available within the year [11].

The advantage of a lithium alloy addition to Al is documented in Figure 7 [12]. The addition of one weight percent lithium (~3.5 atom percent) to aluminum decreases the density by ~3% and increases the elastic modulus by ~6%, hence giving a substantial increase in the specific modulus (E/ρ). Since the solubility of lithium in aluminum is relatively high (~4 wt.% at the eutectic temperature in the Al-Li binary, somewhat less in ternary alloys) Li can be added in sufficient quantities to have an effect that is significant in the engineering sense. Moreover, as shown in Figure 8 [13], if alloys having greater than ~1.5 wt.% Li are aged at intermediate temperature the alloy precipitates a coherent, intermediate phase, Al_3Li (δ') that can be used in combination with precipitates containing ternary additions to harden the alloy to strength levels competitive with those of the aerospace Al alloys.

These basic advantages of the Al-Li system have been known for a very long time [14]. The first U.S. patents on Al-Li alloys were issued in the 1920's, and the first commercial aerospace Al-Li alloy, alloy 2020 (Al-4.5 Cu-1.1 Li-0.5 Mn-0.2 Cd) was used as long ago as 1958 in the structure of the RA-5C Vigilante fighter. While alloy 2020 gave satisfactory performance in the Vigilante, subsequent fracture toughness testing revealed that the alloy is susceptible to brittle fracture, and has a strength-toughness combination that is decidedly inferior to those of the better aerospace aluminum alloys (Figure 9). The alloy was eventually withdrawn.

Fundamental studies on the fracture of 2020 and similar alloys showed that their low toughness is due to brittle fracture along the grain or subgrain boundaries, and identified several microstructural

sources for this embrittlement [15,16]. The two dominant problems appear to be the precipitation of intermetallic phases along the grain boundary and the marked planar slip in the alloy, which creates stress concentrations on the grain boundaries. The intergranular precipitates include both phases that arise from impurities in the alloy, predominantly Fe and Si, and the incoherent forms of the alloy phases, such as δ(AlLi), $T_1(Al_2CuLi)$, and Al_2LiMg. These precipitates tend to embrittle the boundary, and simultaneously extract Li from the boundary region to form precipitate-free zones. The planar slip is largely due to the $L1_2$ structure of the δ' phase, which has the consequence that a pair of basal plane dislocations in the FCC matrix constitute a total dislocation in the ordered precipitate. Matrix dislocations hence tend to pair and to shear and weaken the precipitates as they pass through, promoting planar slip.

Further research identified metallurgical approaches to alleviate these problems [16,17]. It was found that precipitate-induced intergranular fracture can be substantially reduced by lowering the allowable content of Fe and Si in the starting alloy, by controlling processing to avoid the intergranular precipitation of the stable Al-Li and Al-Cu phases, and by preventing recrystallization during processing, using a combination of a small Zr addition and careful control of the processing conditions. The problem of planar slip can be partly overcome by the controlled co-precipitation of coherent Al-Cu or Al-Cu-Li intermetallics. These are interspersed with the δ' and interfere with cooperative dislocation glide.

These metallurgical modifications have been used by Alcoa Aluminum and combined with advances in Al-Li ingot casting technology to create a series of low-density alloys that approximate the properties of such existing aerospace aluminum alloys as 2024-T6 and 7075-T6 [11]. An example is Alcoa CW56, Al-2.7Cu-2.2Li-0.12Zr, which can be treated so that it very nearly reproduces the strength and toughness of 7075-T6 (figure 9), with an apparently improved resistance to fatigue and stress corrosion cracking. This alloy is expected to be commercially available by the end of 1984. Other aluminum producers have similar efforts underway. Aerospace companies, such as Boeing Aircraft [18], have large programs in place to utilize these alloys as replacements for the higher density 7075-T6 and 2024-T6 in current aircraft, and to incorporate them in future designs that will take advantage of their higher specific moduli.

The future development of Al-Li alloys will proceed in several different directions. An immediate goal is the further improvement of alloy toughness to match the properties of the existing high-toughness aerospace alloys such as 2324 and 7475 [9]. To achieve this goal it will probably be necessary to understand and overcome the inter-subgranular fracture that appears in the most promising of the existing alloys. A second goal is the development of highly formable alloys to minimize scrap and decrease the 'as-flown' cost of Al-Li parts. For example, there is active research on superplastic alloys based on Al-Li [19]. A long-range goal is to create suitable alloys with substantially lower density. The barrier in this case is the limited solubility of Li in Al, and the decrease in Li solubility when beneficial ternary species, such as Cu and Mg, are added to the alloy. This problem is being

attacked with rapidly-solidified powder technology in several laboratories [16,20].

C. Formable Steels for Manufacturing

In most applications metal alloys must be formed or shaped into a final part. The formability of the metal largely determines the difficulty of the forming process, the extent of final machining or finishing that must be done, the scrap produced, and the number of independent parts that must be used to construct a device of complex shape. The current emphasis on low-cost, light weight manufactured products has created a variety of needs for highly formable structural alloys. The most obvious needs are in the automotive industry, where vehicle weight must be decreased to meet fuel conservation goals while vehicle safety must be improved and unit costs must be kept low to meet international competition, and in the aerospace industry, where the need to minimize structural weight requires the manufacture of parts with complex geometries.

The problem of designing formable alloys for industries like the automotive industry is a particularly difficult one, since the economics of the industry dictate that the dominant alloys are inexpensive sheet steels, the forming requirements are severe, and the forming operation is done at room temperature. The alloys must sustain large plastic strain without necking or failure at room temperature. The difficulty in designing such alloys follows largely from the fact that we do not yet have a good scientific understanding of the metallurgical factors that determine the response metal to large plastic deformation at low temperature.

The essence of the problem appears in the one-dimensional case, and is apparent from a consideration of the simple engineering stress-strain curve shown in Figure 10. The curve shows typical mechanical behavior: elastic deformation to yielding at the yield stress, then stable plastic deformation until plastic instability, or necking, sets in at the ultimate tensile stress, then rapid neck-down and fractures. The formability of an alloy can be roughly inferred from its plastic elongation to fracture, which is almost completely determined by its uniform elongation prior to necking. The necking phenomenon is, however, caused by macroscopic plastic instability; it does not represent any fundamental change in the microscopic behavior of the alloy. This is apparent from the true stress-strain curve shown in the lower part of the figure. The alloy yields, and then hardens monotonically to failure. Necking occurs when the rate of hardening is no longer sufficient to balance the increase in true stress when local plastic deformation causes a net decrease in the specimen section, that is, when the Considere Criterion

$$d\sigma^*/d\varepsilon^* = \sigma^* \qquad (1)$$

is satisfied, where σ^* is the true stress and ε^* is the true strain. To control necking, and hence control formability, one must be able to control the rate of work hardening in the alloy.

The problem is that the metallurgical theory of plastic deformation and work hardening in real alloys is poorly developed. The knowledgeable metallurgist can say a great deal about yielding and fracture and how they are controlled by the details of the microstructure, but is reduced to very rough, qualitative statements when asked to predict or control the behavior that lies between these two limits of plastic deformation. The microstructural determinants of work hardening and, hence, formability are simply not well understood.

Despite the dearth of fundamental knowledge, there have been major strides in the development of new formable steels in recent years [21,22]. The breakthroughs have been based largely on continuum models. While several different models have been used to motivate these efforts, they may be roughly interpreted as follows.

The Considere Criterion can be regarded as an equation that determines the ideal form of the true stress-strain curve for a formable alloy. If the work-hardening rate ever falls below the flow stress the sample will neck down and fracture. But it is almost equally bad for the work-hardening rate to exceed the flow stress, since it will then add an unnecessary increment to the flow stress that requires a still higher work-hardening rate to maintain stable plastic deformation. It follows that the ideal alloy would obey Eq. (1) over the whole plastic range, and would hence have a true stress-strain curve that is described by the equation

$$\sigma^* = \sigma^*_Y \exp(\varepsilon - \varepsilon_Y) \qquad (2)$$

This equation is plotted in Figure 11, and compared to a schematic representation of the the true stress-strain curve of a typical steel, which tends to have a parabolic shape. It is clear that the real alloy wastes work hardening. The rate of work hardening is rapid when the flow stress is small, but decreases when the flow stress is large. The ideal curve, on the other hand, is concave upward, and has a work-hardening rate that increases with the flow stress. A comparison of the two suggests that formability be improved by decreasing the strength of the steel so that work hardening saturates at a smaller value of the flow stress. Consistent with this view, the uniform elongation of a typical steel decreases monotonically with its tensile strength, as illustrated in Figure 12 [23].

But given the simultaneous need for low weight and high structural strength in safety-critical components, there is a demand for alloys that combine formability with high strength. The continuum analysis suggests at least three metallurgical approaches that may accomplish this. The first approach is to identify and eliminate any microstructural flaws that cause a decrease in the work-hardening rate at high strains. The most common flaws are inclusions in the alloy that crack or lose coherence under strain to produce voids. These can be eliminated by increasing the purity of the alloy or modified in shape or composition to render them innocuous. This approach has been successfully used to produce high-purity or 'inclusion shape controlled' alloys with improved formability.

The second approach is to process the alloy so that it becomes a composite of distinct microstructural constituents. If these are all deformable, but have different yield strengths, then they contribute sequentially to plastic deformation and work hardening. In a first approximation in which the constituents did not influence one another, each would begin to deform when the flow stress became equal to its yield strength, producing a stress-strain curve like that diagrammed in Figure 13, in which the alloy has a high, sustained work hardening rate and a large uniform elongation. This is essentially the approach that underlies the 'dual phase' steels [24-26], in which the alloy is given an intercritical anneal in the two-phase ferrite-austenite region of its phase diagram to produce a mixed microstructure of tempered ferrite, retransformed ferrite, fresh martensite, and retained austenite. The complex microstructures that are produced by three variants of the intercritical-annealing treatment are illustrated in Figure 14 [27].

The third approach is to introduce a distribution of metastable austenite that transforms under strain to a dislocated martensite phase. Since the austenite-martensite transformation in steel involves a significant shape change, the transformation accomplishes plastic deformation. But since the transformation yields a deformable product it creates a microstructure that is capable of further work hardening. The introduction of a distribution of retained austenite into a microalloyed steel can hence contribute a small 'free' elongation, improving formability [23].

All three of these metallurgical techniques are used in the modern 'dual-phase' steels that are now finding use for high-strength parts in automobiles. The alloys combine a low inclusion content with a multiconstituent microstructure produced by an intercritical temper. They can be made to have exceptional combinations of strength and elongation, as shown in Figure 12. Until recently 'dual-phase' steels of consistent quality were difficult to obtain from domestic mills, but the recent construction of continuous-annealing sheet steel lines at Inland Steel and at Bethlehem Steel is expected to make them more widely available.

While the success of the dual-phase steels is encouraging, these steels were designed by avoiding, rather than confronting, the fundamental problem of formability: the inappropriate shape of the stress-strain curve of a single-phase alloy. There may, therefore, be dramatically different approaches to improved formability that remain unexplored. It is entirely possible that the work-hardening characteristics of microalloyed steel are inherent and relatively immune to microstructural manipulation. But it is equally possible and, history suggests, more likely that fundamental research into the sources of work hardening will reveal microstructural relations that can be profitably used to design alloys with substantially improved forming characteristics.

CONCLUSION

This paper has briefly covered three areas in which the systematic design of new metal alloys promises to solve important technical problems. It did not treat a host of parallel developments that are equally important and exciting in such areas as high-temperature structural

alloys, oxidation, corrosion, and wear-resistant alloys, high-strength structural alloys, magnetic alloys and films, and electrical conductors and superconductors. But the pattern of development in each of these areas is basically the same: the coupling of fundamental science and materials characterization to clarify the microstructural sources of important engineering properties, then the systematic manipulation of microstructure to create new alloys that satisfy important engineering needs.

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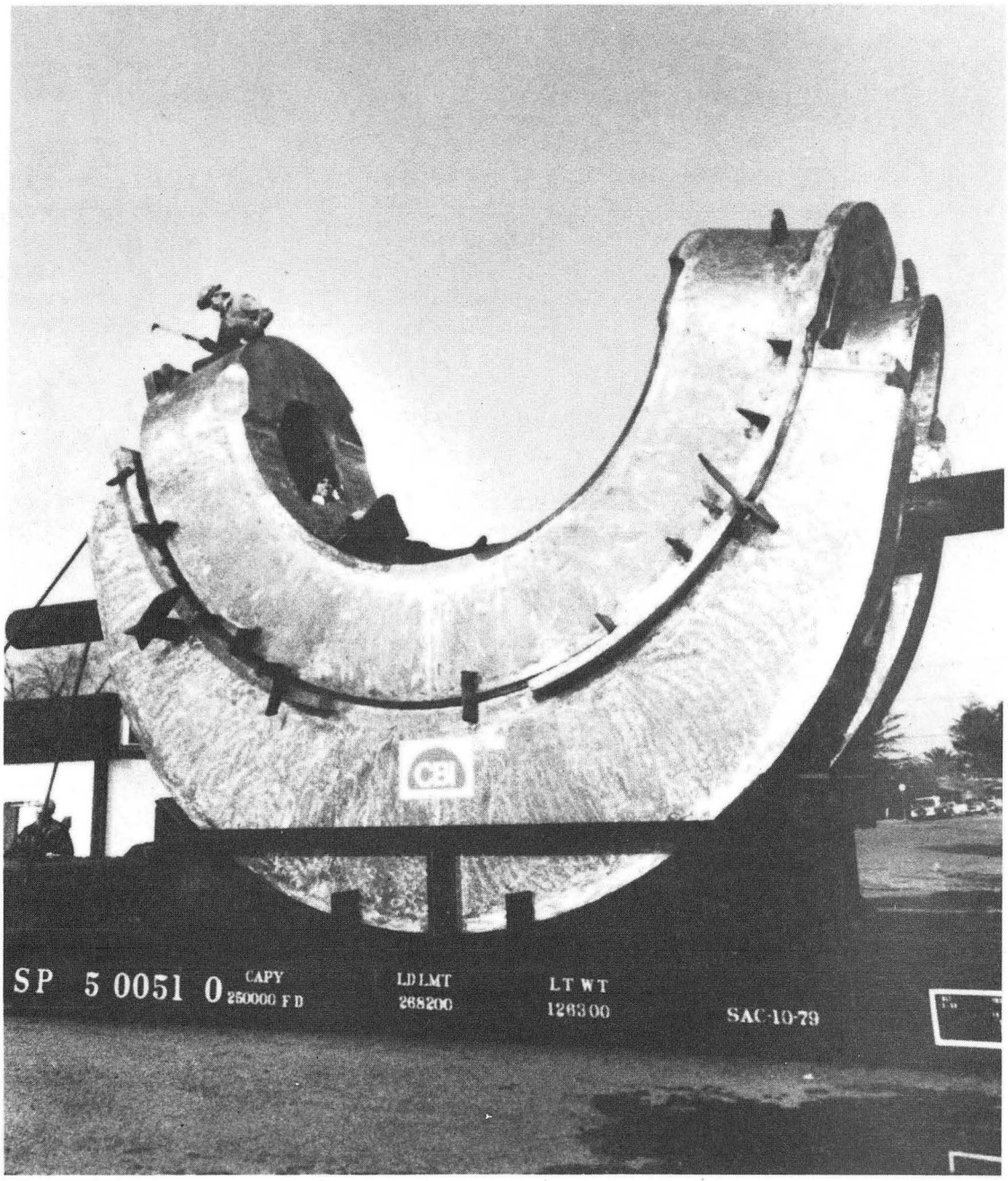
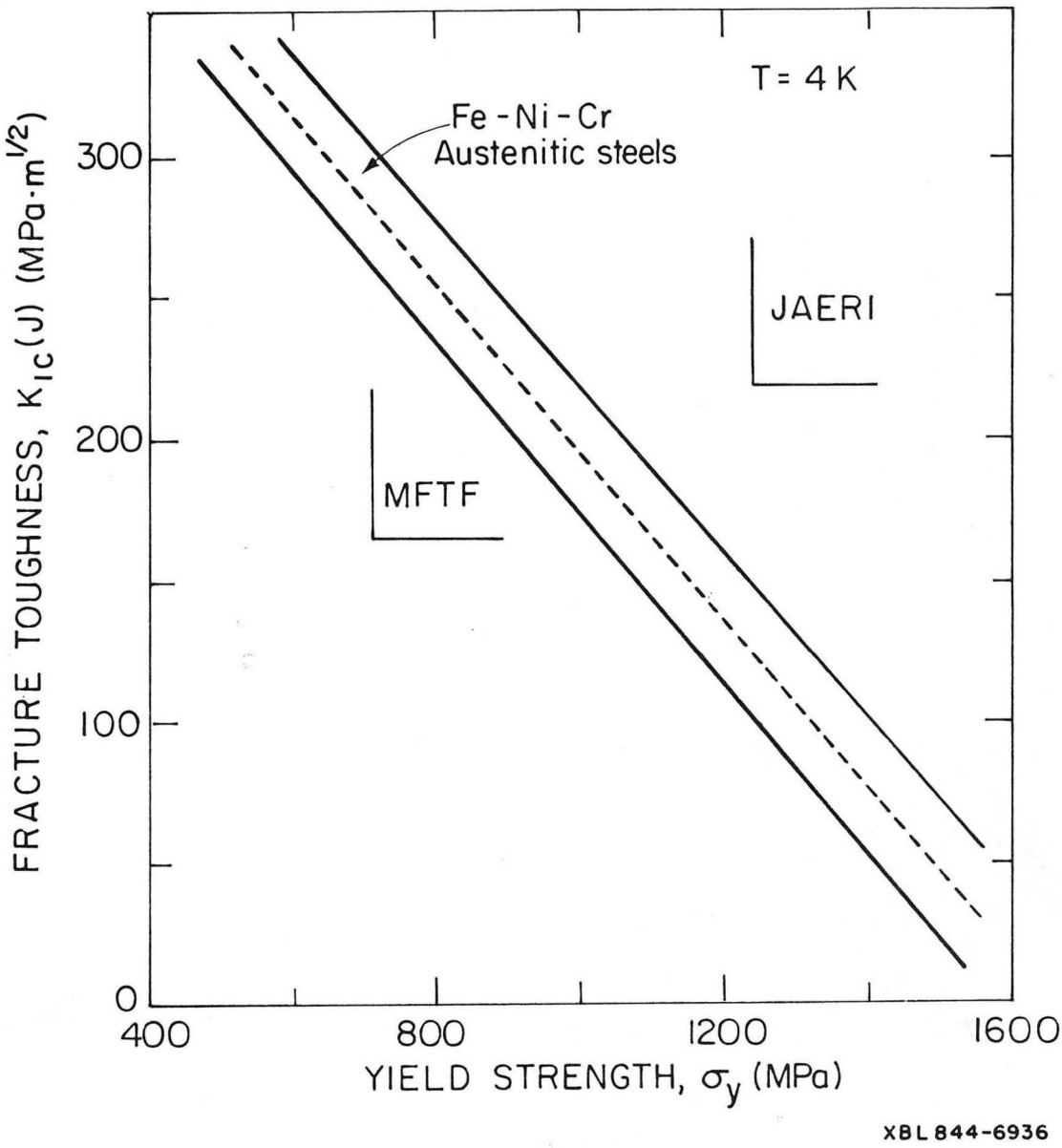
27. Courtesy of G. Thomas, Univ. of California, Berkeley.

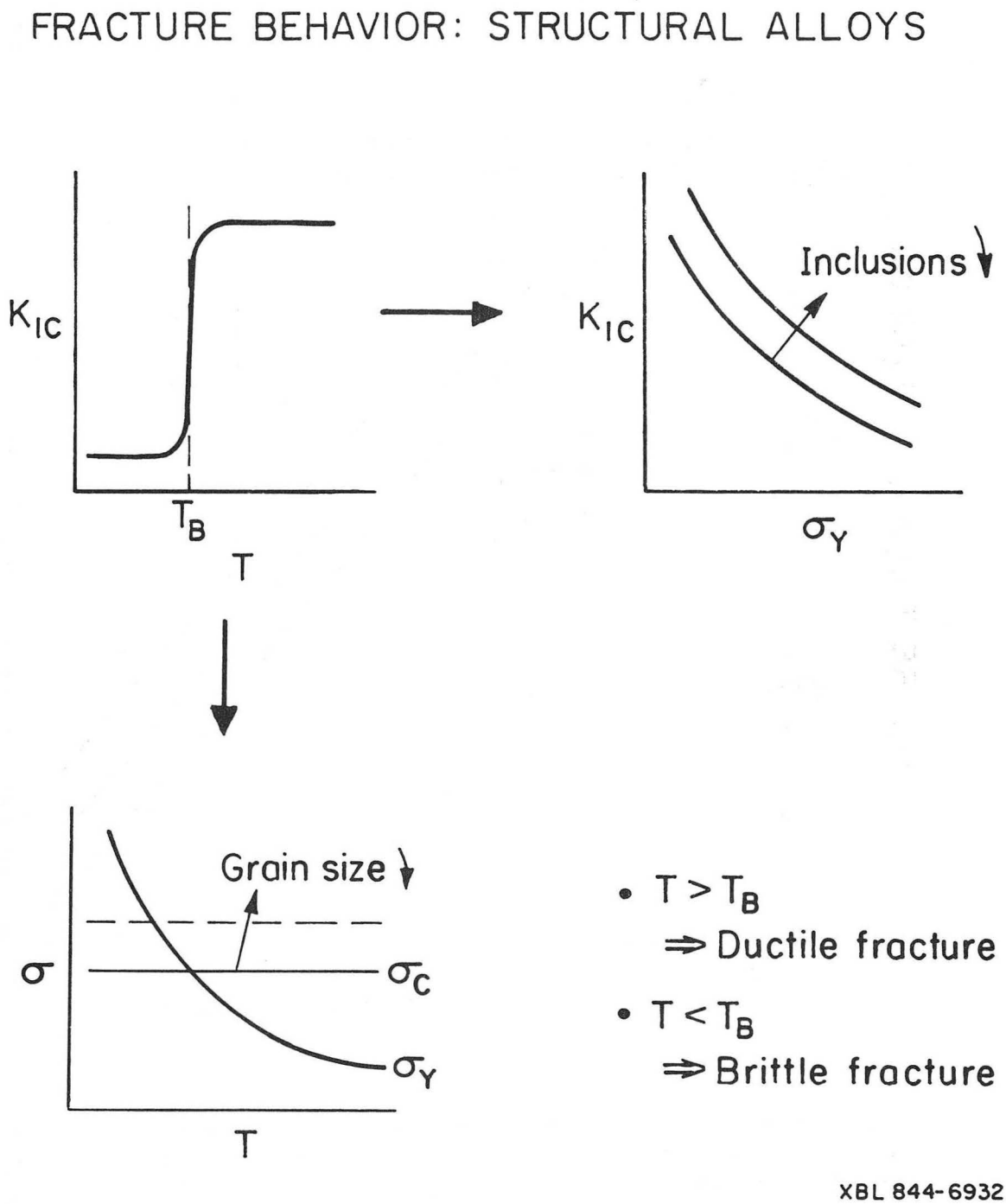


CBB 844-3207

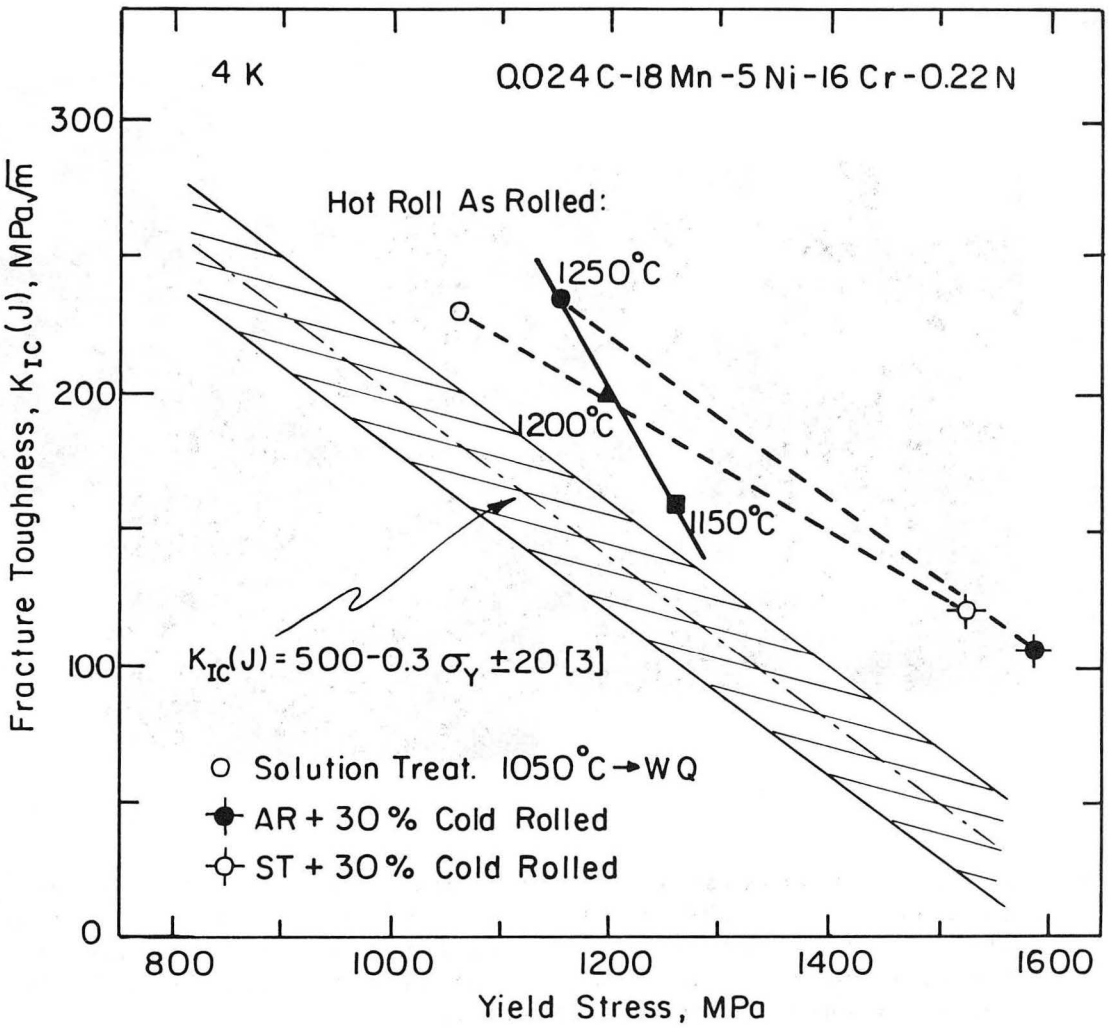
1. One section of the ying-yang superconducting coil set for the Mirror Fusion Test Facility at LLNL



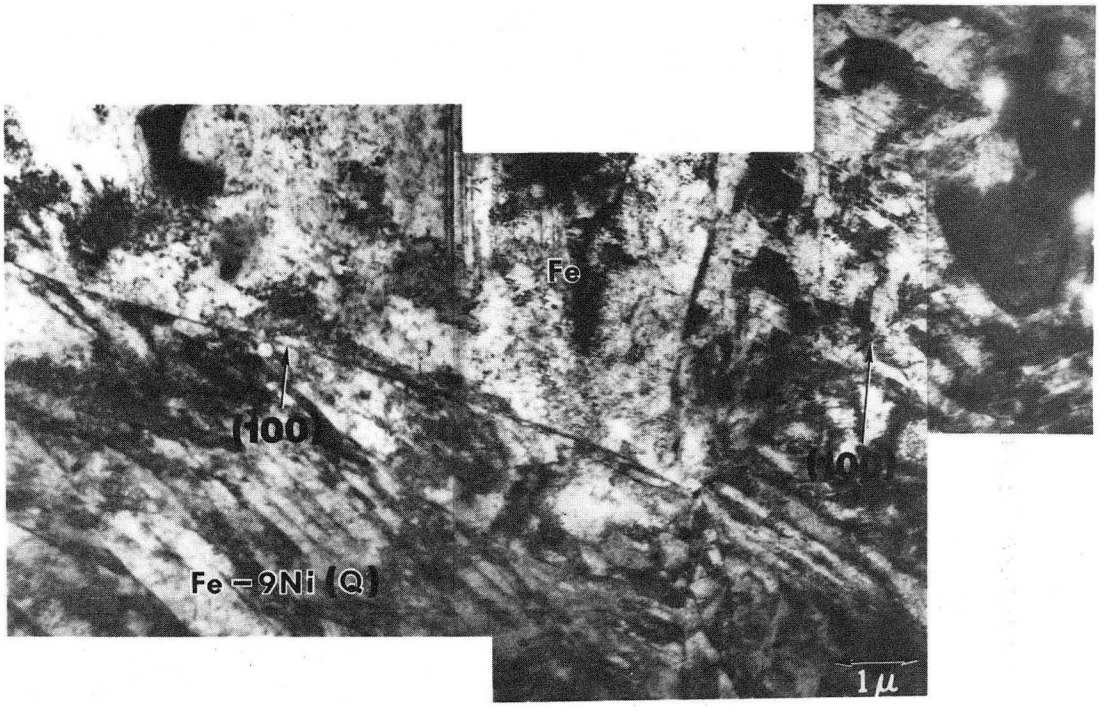
2. The strength-toughness trend line for conventional stainless steels at 4K. Specifications for the MFTF-A coil case and the JAERI tokomak are labelled.



3. Fracture behavior: Structural Alloys

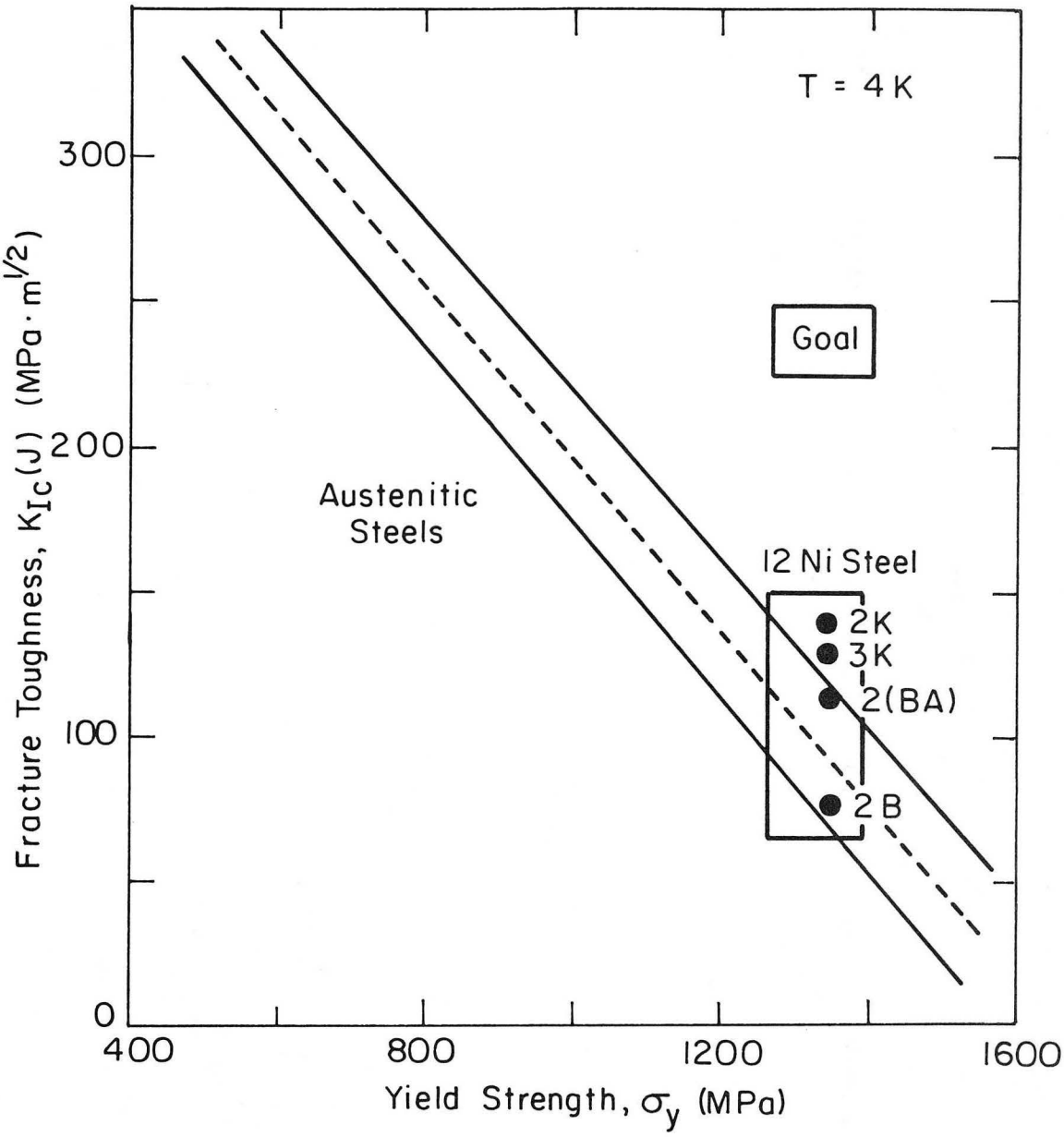


4. Strength-toughness data at 4K for a nitrogen-strengthened 18Mn-16Cr-5Ni steel.



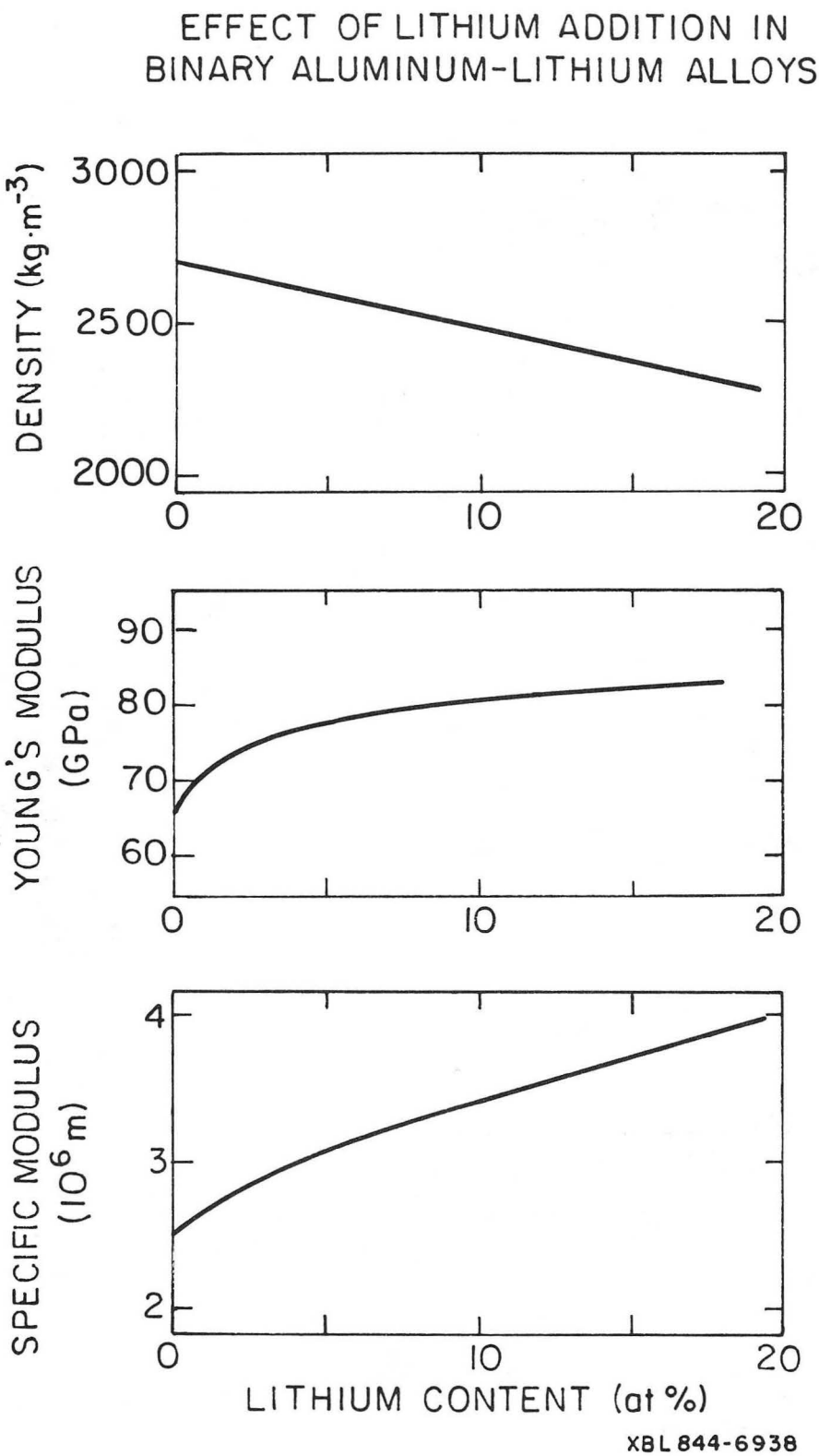
XBB 812-1672

5. A profile transmission electron micrograph showing cooperative cleavage along (100) planes that traverse packets in an Fe-Ni steel. The fracture surface is labelled, and branches at the packet boundary. The upper portion of the figure is an Fe coating deposited onto the fracture surface.

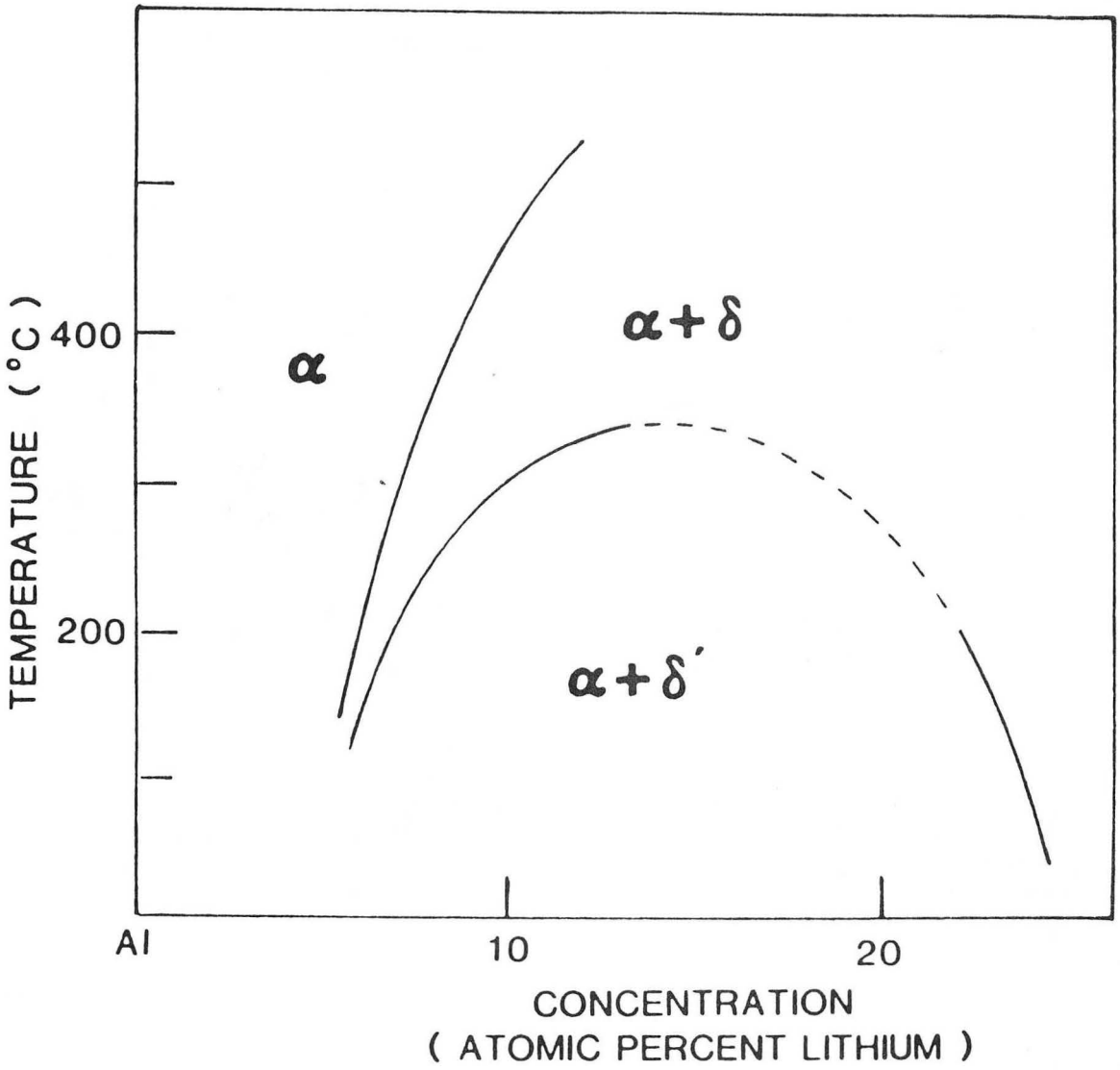


XBL 836-5849

6. The 4K properties of heat-treated Fe-12Ni-0.25Ti compared to those of the conventional stainless steels and those required for the JAERI tokamak design.

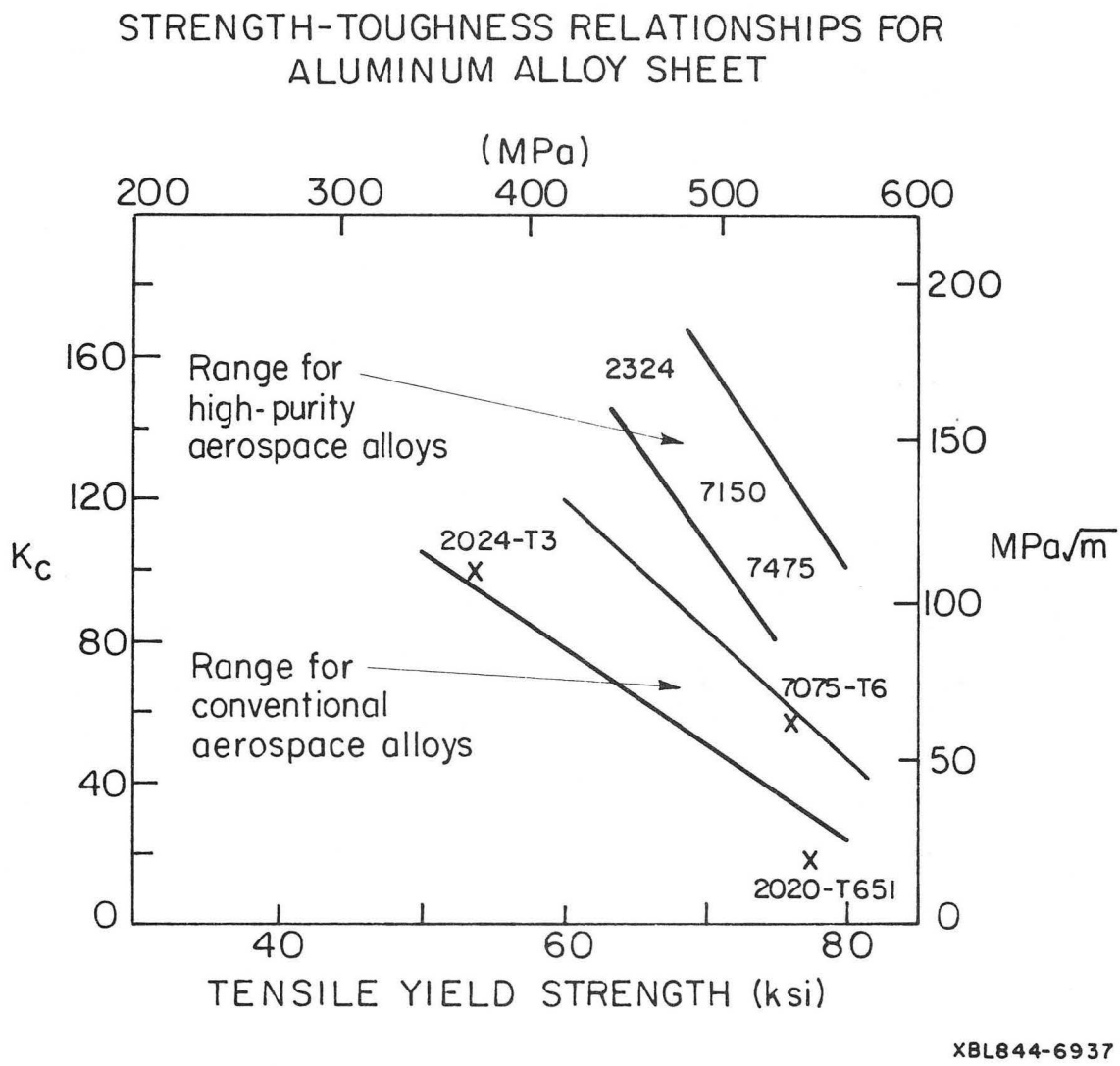


7. Effect of the lithium addition in binary aluminum-lithium alloys.

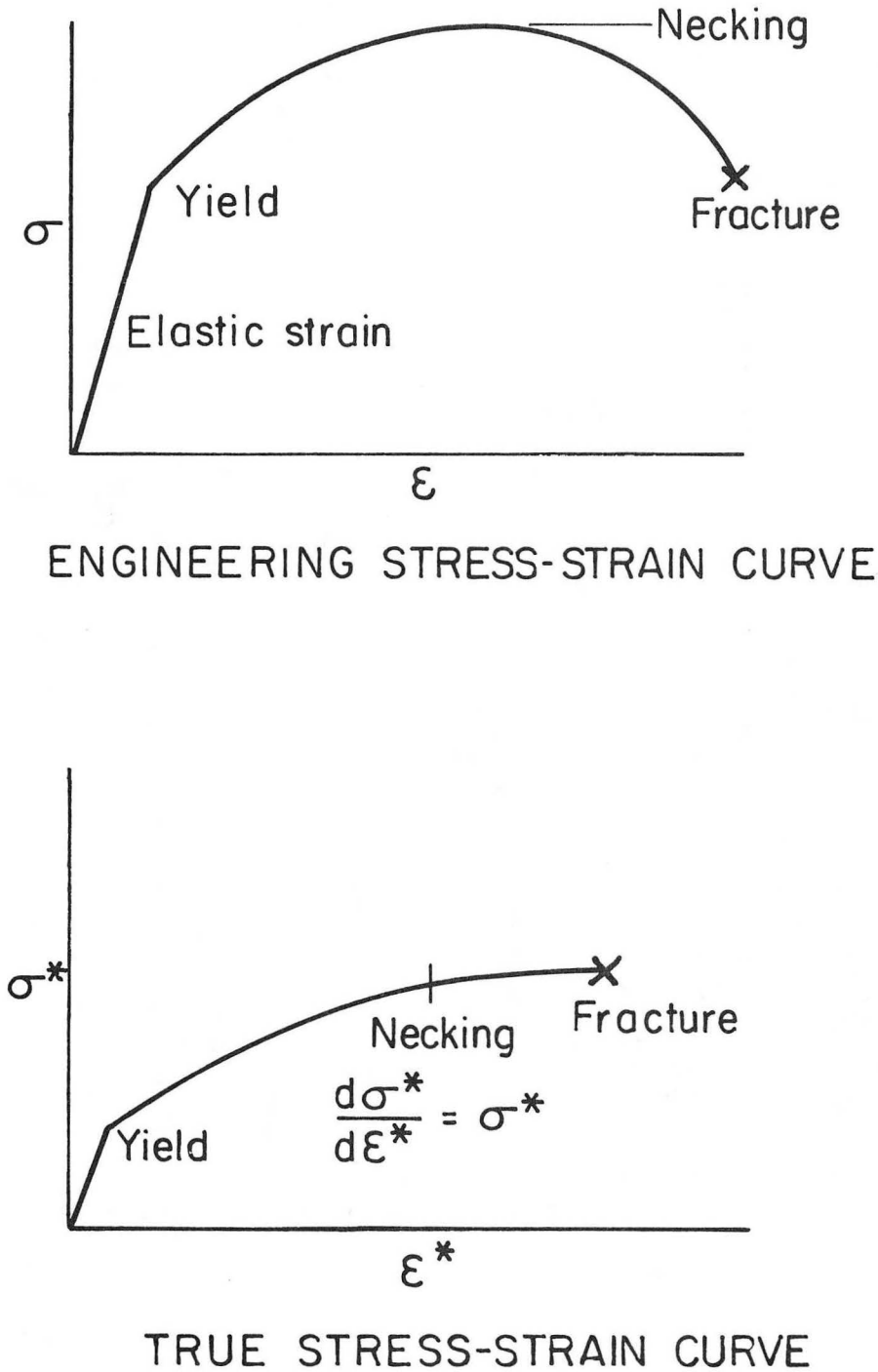


XBL 845-1665

8. Section through the aluminum-lithium phase diagram showing the metastable δ′ solvus line.

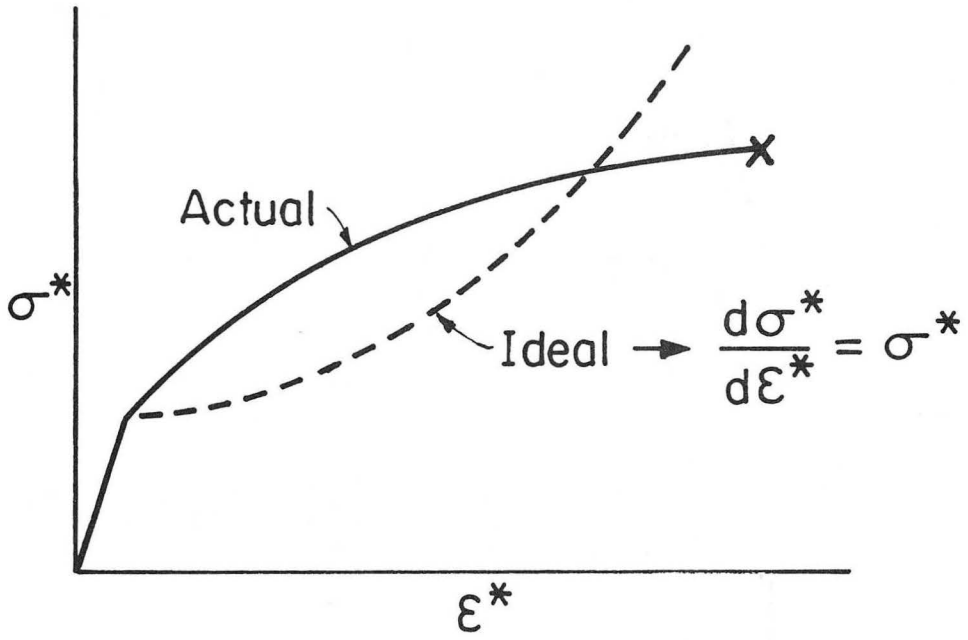


9. Strength-toughness relationships for aluminum alloy sheet



10. Engineering and true stress strain curves

TYPICAL ALLOYS WASTE WORK HARDENING

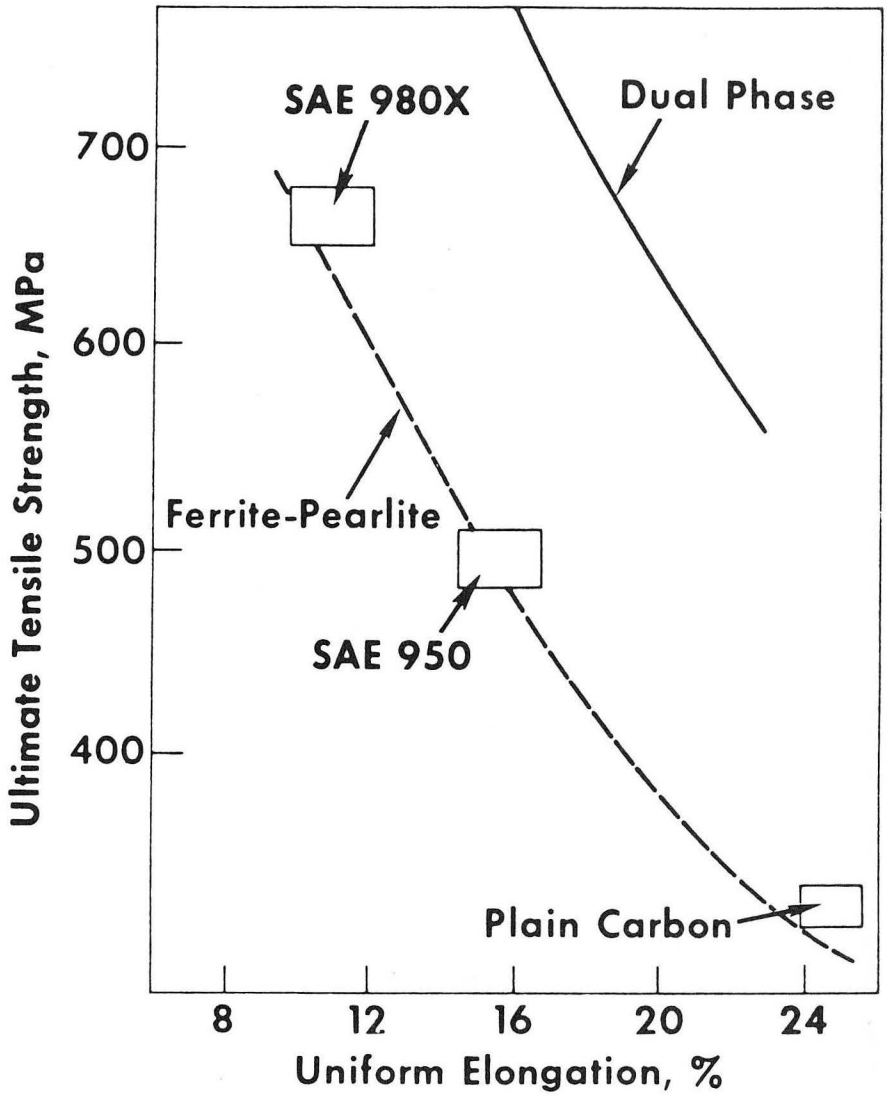


$\frac{d\sigma^*}{d\varepsilon^*}$ high when σ^* low

$\frac{d\sigma^*}{d\varepsilon^*}$ low when σ^* high $\Rightarrow$ instability

XBL844-6934

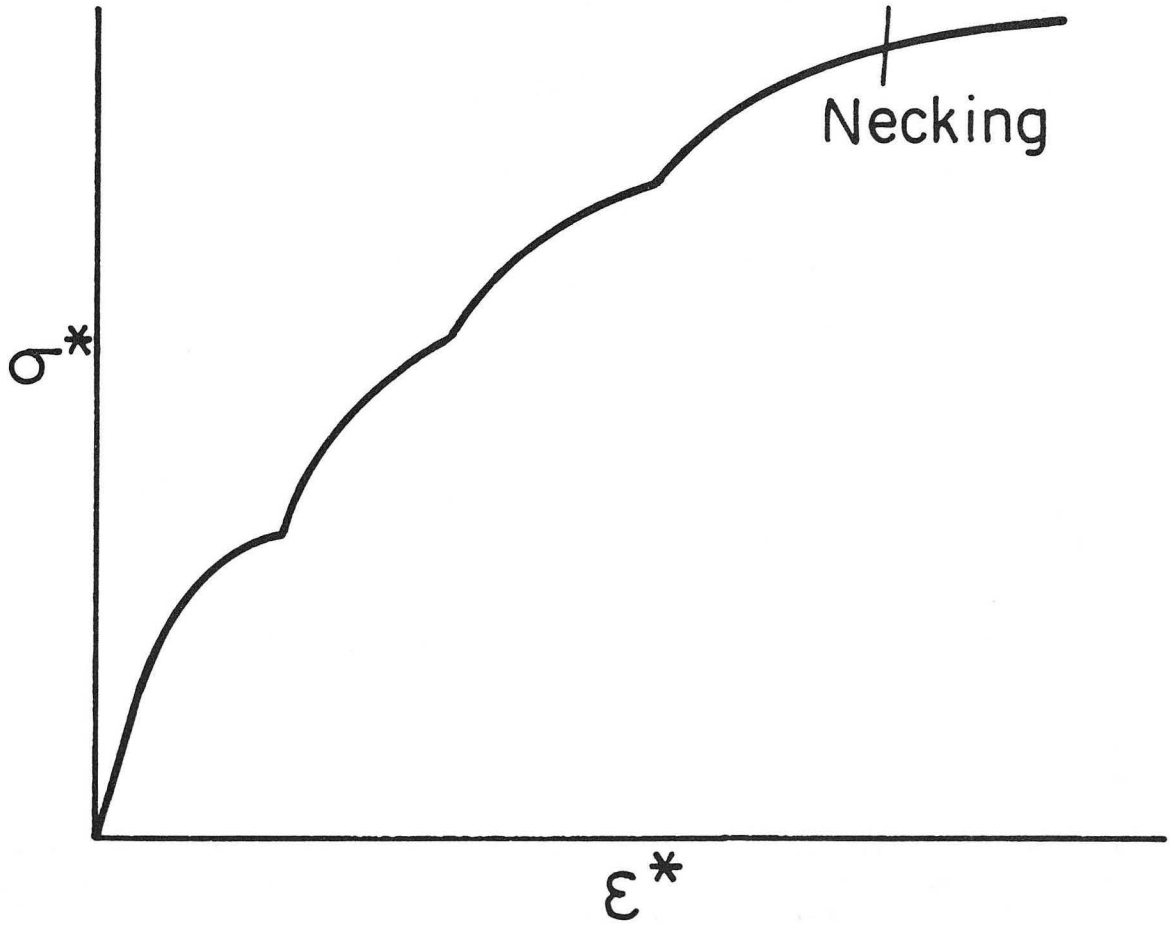
11. Typical alloys waste work hardening



XBL 845-1664

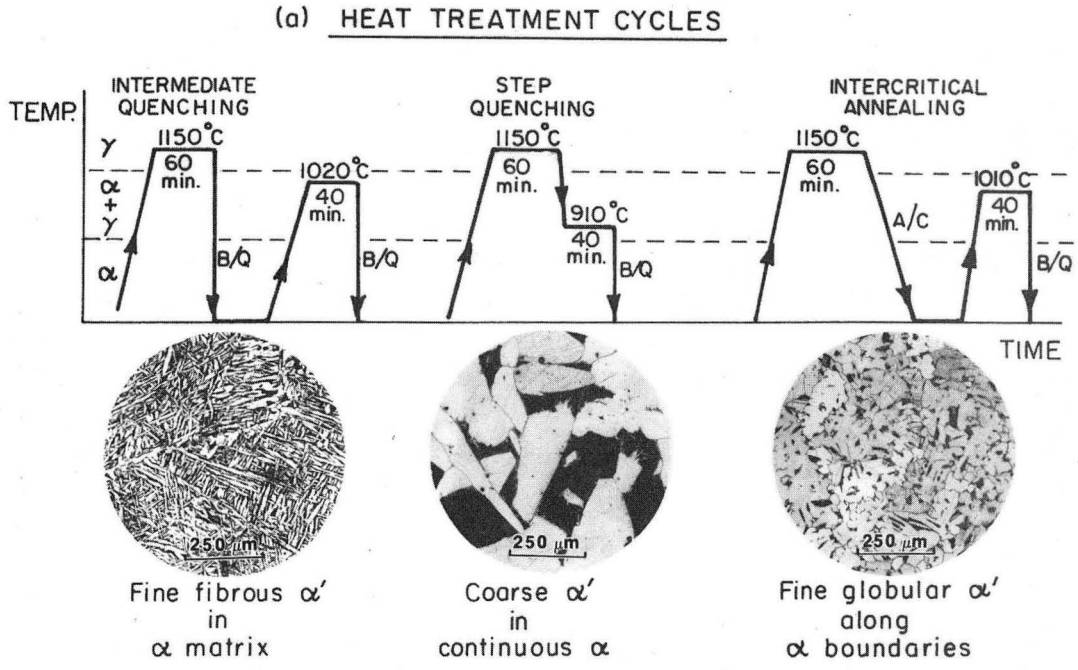
12. Strength-ductility relationship for plain carbon, ferrite-pearlite and HSLA steels. The more favorable relationship of the dual-phase steels is plotted for comparison.

IDEALIZED STRESS-STRAIN CURVE FOR A MULTI-PHASE ALLOY



XBL 844-6935

13. Idealized stress-strain curve for a multi-phase alloy



XBB 838-2300

14. Heat treatment cycles and dual phase microstructures

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