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Koo, J.Y.

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J. Y. Koo, B. V. Narasimha Rao and G. Thomas

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DESIGN OF SUPERIOR STEELS WITH DUAL PHASE STRUCTURES

J. Y. Koo,* B. V. Narasimha Rao and G. Thomas

Materials and Molecular Research Division,
Lawrence Berkeley Laboratory, and
Department of Materials Science and Mineral Engineering,
University of California, Berkeley, CA 94720

I. INTRODUCTION

Strength, toughness and ductility are undoubtedly the most important properties specified for structural steels unless the application involves aggressive environments. The major difficulty in optimizing these properties comes from the fact that strength is usually inversely related to toughness and ductility: the increase in the former is achieved at the expense of the latter and vice versa. This is true in the majority of cases when relatively inexpensive alloying and processing are sought for a practical alloy development.

This paper is aimed at emphasizing our current alloy design programs which utilize the concept of two phase steels as a means of optimizing these mutually exclusive properties. The underlying principle here is to utilize composites whereby the advantages of the second phase are optimized while the less desirable features of this phase are simultaneously mitigated by the presence of the other constituent phase. The size, distribution, shape and volume fraction of the second phase critically control the mechanical behavior of the dual phase systems. As a consequence, these structures offer a degree of metallurgical

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* Now at Rutgers University, Department of Mechanics and Materials Science, Piscataway, N.J. 08854

flexibility that is absent in single phase structures or many precipitation strengthened systems for attaining optimum sets of mechanical properties.

Examples are presented here of the martensite/austenite mixture designed for the optimum combinations of utltrahigh strength and toughness properties of medium carbon steels, and martensite/ferrite structure for high strength and good formability in low carbon steels.

II. MARTENSITE/AUSTENITE STRUCTURE

While the strength of martensitic steels can be most effectively increased by raising the carbon content of these steels, their toughness deteriorates monotonically.[1,2] This becomes the limiting factor in the use and development of such high strength steels. A simple calculation from a fracture mechanics viewpoint indicates that at the 200,000 psi yield strength level, a minimum of 80 ksi-in$^{1/2}$ plane strain fracture toughness is needed for a critical flaw size of 0.1" if 60-80% of available strength is to be utilized.

From our systematic studies[1-4] of the structure-property relations in quenched and tempered steels, an experimental steel of composition Fe/4Cr/0.3C, which combines ultra-high strength and good toughness has been successfully developed through control of microstructure and heat-treatment. An important microstructural feature among others identified in the new experimental steel with the use of careful methods of transmission electron microscopy is the presence of small quantities ($\lesssim$ 1%) of retained austenite in the form of extremely narrow thin films along the dislocated lath martensite boundaries (Fig. 1, schematic). Thus, in this system, the major phase is the relatively stronger but less ductile martensite, and the minor phase is the relatively tougher retained austenite. The martensite brittleness is related to carbon and twinning.[1,2] The carbon content of the steel should be less than about 0.35 w/o in order to avoid substantial twinning in martensite and the consequent brittleness. The presence of retained austenite, depending on its mechanical and thermal stabilities,[5] can provide a direct benefit of increased crack propagation resistance through one or a combination of the following mechanisms: (i) crack branching, (ii) crack blunting, and (iii) transformation induced plasticity. In addition indirect benefits include high solubility of interstitials (e.g. carbon), prevention of brittle lath boundary carbide formation and the presence of a highly coherent retained austenite/lath martensite interface.[3] The FCC austenite phase also serves to break the continuity of the cleavage planes across various laths in a packet.

Since the emphasis in these steels is on crack propagation resistance rather than elongation ductility, the volume fraction of the minor phase can be quite small ($\gtrsim$5%) and yet have a significant influence on the fracture toughness. However, at these small volume fractions the advantages of the minor phase (austenite) become most effective when present as continuous thin films rather than when it is present as discontinuous blocky "particles". The morphology of the latter case occurs with the formation of reverted austenite in maraging and other alloy steels containing a high concentration of strong FCC stabilizers such as Ni, for example Fig. 2.

Fe/Cr/C steels were designed to obtain the morphology of Fig. 1. Subsequently, in order to control the amount and stability of retained austenite, keeping in mind that the improved toughness gained through the retention of austenite should be obtained without sacrificing the ultrahigh strength level, the base experimental steel (Fe/4Cr/0.3C) was modified with FCC stabilizing elements. The specific example discussed here is the quaternary additions of Mn up to 2 w/o. The processing of the steel is as follows:

1. Austenitizing at 1000-1100°C (1 hr./inch thickness) to dissolve all alloy carbides.
2. Oil quench to induce auto-tempering
3. Temper if higher toughness is required.

The typical microstructure of the steel in the as-quenched state is shown in Fig. 3. The improved fracture toughness with increased Mn content compared to Fe/4Cr/0.3C base alloys is clearly illustrated in Fig. 4 for both as-quenched and tempered conditions. A similar trend was observed for the impact properties, and Fig. 5 compares the superior combinations of strength and impact energy of the Mn modified experimental steel with those of comparable commercial alloys. It is evident from these property data that the steel can be used in the as-quenched condition <u>without the necessity of normal tempering treatment</u>.[1]

Transmission electron microscopy studies have confirmed that there were no differences in either the martensite morphology or substructure as a result of Mn addition up to 2 wt%. The most significant structural change was the linear increase in the retained austenite volume fraction as a result of increasing amounts of Mn addition (e.g. ~ 0.5% in the base alloy to ~2% in the 2% Mn modified steel). From these and other observations[3,4] made with the microstructure-mechanical property correlations, it is concluded that the improved toughness observed in the 2% Mn modified steel is predominantly due to the increased quantity and stability of retained austenite. The volume fraction of retained austenite, however, must be kept sufficiently low (say $\lesssim$ 5%) so that improved toughness can be obtained without any attendant sacrifice in the ultrahigh strength level.

III. MARTENSITE-FERRITE STRUCTURES

The preceding example represents an attempt at developing ultrahigh strength, tough medium carbon steels in which improvement in toughness at high strength level ($\gtrsim$ 200 ksi) is a crucial factor. The reverse situation can now be considered where the increase in strength is called for while maintaining high levels of ductility or formability, which is the case with low carbon, low alloy steels. The microstructural features developed to achieve these goals were met by designing duplex martensite-ferrite "composites".(6,7) This is the class of HSLA steels now known as duplex or dual phase steels.

The strengthening principle of such structures involves the incorporation of inherently strong martensite as the load carrying constituent in a ductile ferrite matrix.(6) The latter supplies the system with the essential ductility. Here again, the nature of the components is exploited in optimizing the mechanical properties. Since elongation ductility which represents the bulk flow properties of the material is of interest in this system the volume fractions of the relatively ductile ferrite phase are rather large. The principle of heat treatment to produce martensite-ferrite structure is as follows:(6)

1. Austenitize and quench, or normalize.
2. Annealing in the two phase ($\alpha + \gamma$) range
3. Rapid quench to obtain martensite-ferrite composites.

The exact heat treatment can vary(7) depending on the chemical composition of steels and the types of desired morphology, for example Fig. 6. Figures 7(a), and 7(b) illustrate optical and transmission electron micrographs of the desired duplex martensite-ferrite structure developed in Fe/2%Si/0.1%C steels subjected to the duplex heat treatment described above. This duplex steel exhibits superior tensile properties compared to commercially available high strength, low alloy (HSLA) steels, as shown in Fig. 8. Another attractive feature of the duplex structure is that a wide spectrum of strength and ductility combinations are available depending on the volume fraction of martensite which is determined by the tie line corresponding to the holding temperature in the $(\alpha+\gamma)$ two phase region,[6] Fig. 6.

Empirically the strength is given by the mixtures law:

$$\sigma = \sigma_m V_m + \sigma_\alpha(1 - V_m)$$

where σ_m, σ_α are the strengths of martensite (m) and ferrite (α) and V_m is the volume fraction of martensite. The ductility varies inversely with σ. Considerable flexibility is also possible by changing σ_α by precipitation (using carbide forming elements).[7]

The characteristic stress-strain behavior includes fairly extreme work hardening rates and resultant high elongation ductility and high UTS/YS ratio. This results from the nature and properties of each component phase in the duplex steel. The particular advantages of the Fe/2Si/0.1C steel are listed below.

1. The ferrite region is substantially free from interstitials and precipitation, and is thus highly ductile, since dislocations are mobile.
2. The martensite phase is both strong and tough. To attain this, the substructure and hence the carbon content in the martensite should be controlled to be less than 0.35 wt% (as shown in section II above).

3. The martensite/ferrite interface is highly coherent, giving rise to increased efficiency of load transfer from ferrite to martensite. In the Fe/Si/C steels no carbides form at this interface, so no decohesion occurs.
4. The elastic constants of martensite are equal to those of ferrite. As a result there is no localized stress concentration in the elastic range of both phases.

In addition it is also important to take into account the geometry of the martensite phase in the ferrite matrix for optimum property balance, Fig. 6. In this regard, a finer scale (smaller effective grain size) and a discontinuous morphology are considered to be desirable, Fig. 6(d).

IV. SUMMARY AND CONCLUSIONS

In both examples presented here, the optimum two phase microstructure is obtained through the control of solid state phase transformations in selected alloy compositions. The processing involves only thermal treatments without recourse to the expensive thermo-mechanical treatments. In addition, the solid state phase transformation ensures good bonding (coherency) between the constituent phases--a significant advantage over the artificially produced composites.

The concept of duplex steels has been illustrated in achieving unusual property requirements which cannot be met by conventional single phase alloys with comparable compositions. The duplex martensite/retained austenite structures are designed for improved toughness and ultrahigh strength, and the duplex martensite/ferrite structures for high strength with high ductility. In the two examples presented here, although the microstructural combinations are different, the common principle is to utilize the second phase to its advantage while the less desirable features of this phase are simultaneously mitigated by the presence of the other constituent phase. The applications of this principle can be extended to many other material systems for achieving optimum mechanical properties. This work also emphasizes the need for careful transmission electron metallographic characterization of microstructures at the highest attainable resolutions in order to gain a fundamental understanding of microstructure-property correlations without which systematic design of structural alloys is not easily achieved.

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FIGURE CAPTIONS

Fig. 1. Schematic showing desired duplex microstructure consisting of major phase martensite contributing to strength and minor phase retained austenite providing improved toughness.

Fig. 2. Typical morphology of reverted austenite revealed by the bright-field (a) and dark-field (b) micrographs. Example taken from quenched and tempered (above 1000^{O}F) specimens of 14 Co/10Ni/3Cr/1Mo/0.16C steel.

Fig. 3. Bright-field (a) and dark-field (b) images showing retained austenite in Fe/4Cr/0.3C/2Mn as-quenched alloy.

Fig. 4. Plane strain fracture toughness vs. w/o quaternary alloying to the Fe/4Cr/0.3C alloy.

Fig. 5. Comparison of Charpy impact energy vs. tensile strength of experimental quaternary alloys and equivalent commercial alloys.

Fig. 6. Schematic illustration of microstructures expected to result from the transformation paths indicated. Light regions represent ferrite and shaded regions represent martensite (or other austenitic decomposition products).

Fig. 7(a). Optical micrograph of Duplex Ferrite-Martensite (DFM) structure developed in Fe/2%Si/0.1C alloy.

Fig. 7(b). Transmission electron micrograph showing fibrous DFM structures developed in the 2 pct Si steel. Two parallel needles are martensite packets surrounded by ferrite with a high density of dislocations.

Fig. 8. Tensile properties of the duplex 2% Si steel compared with those of commercial HSLA steels.

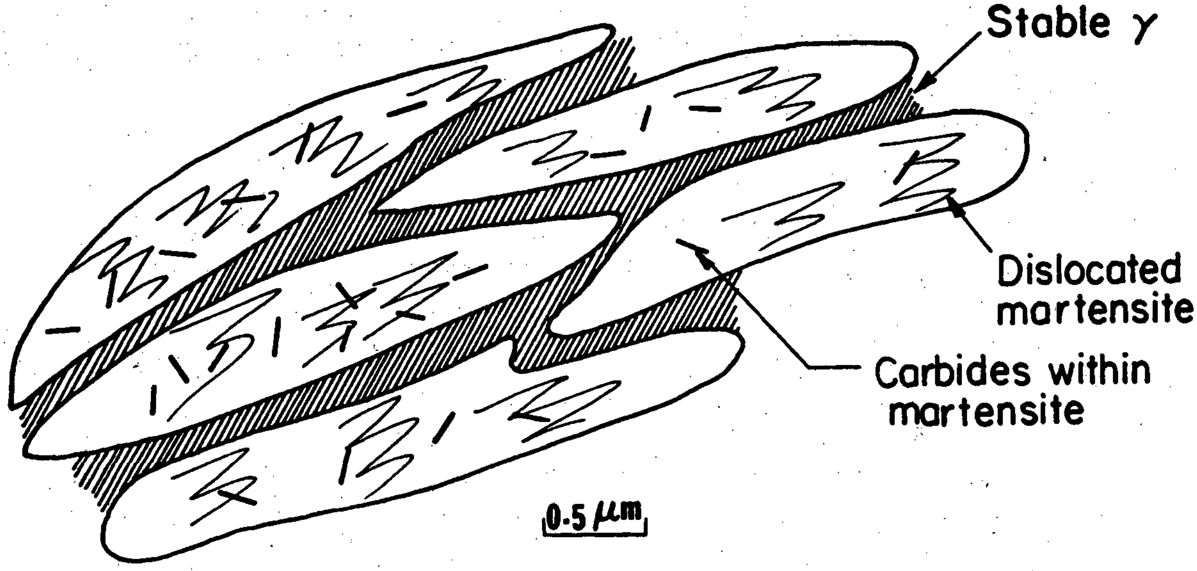

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Fig. 1

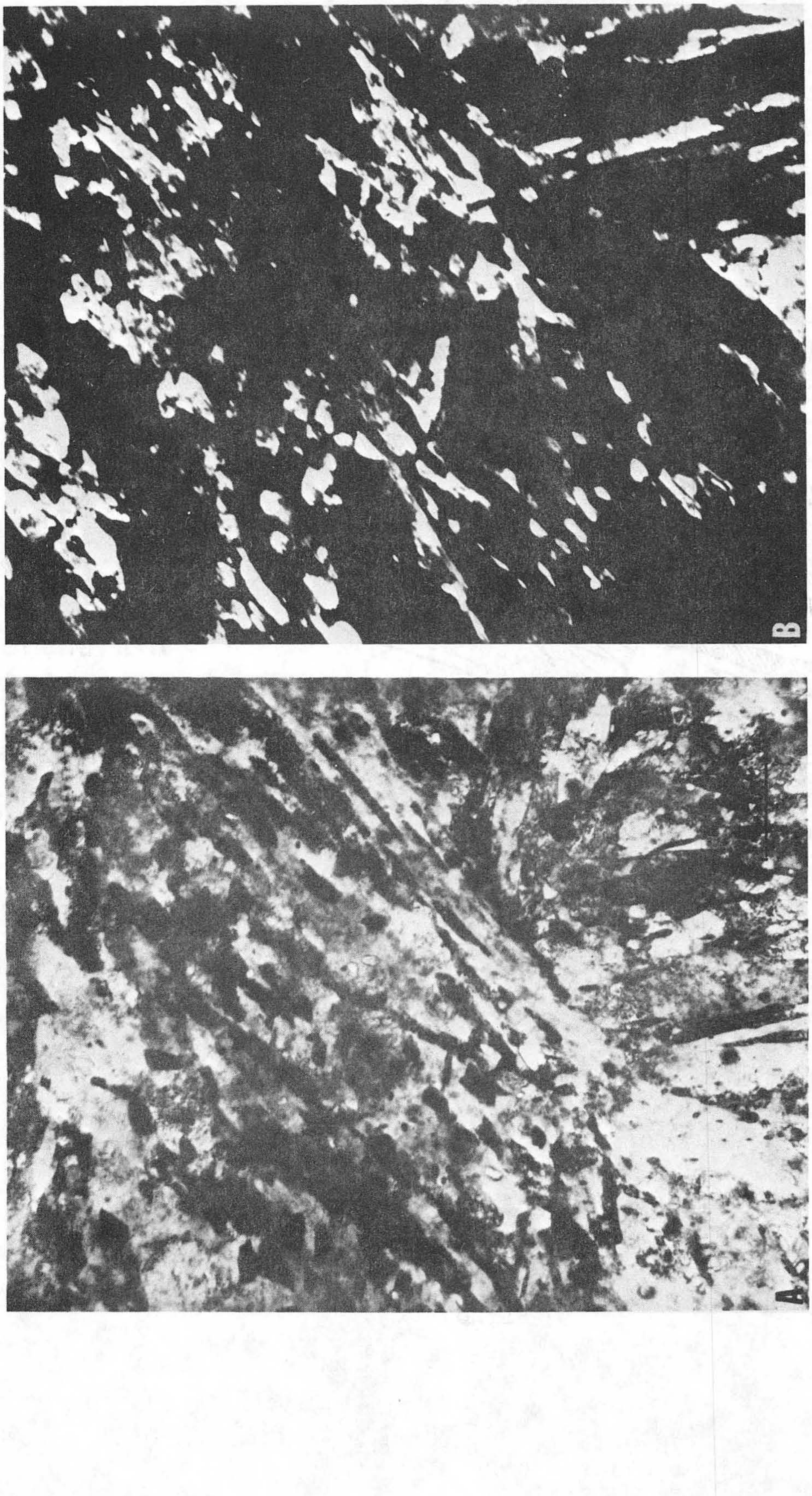

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Fig. 2

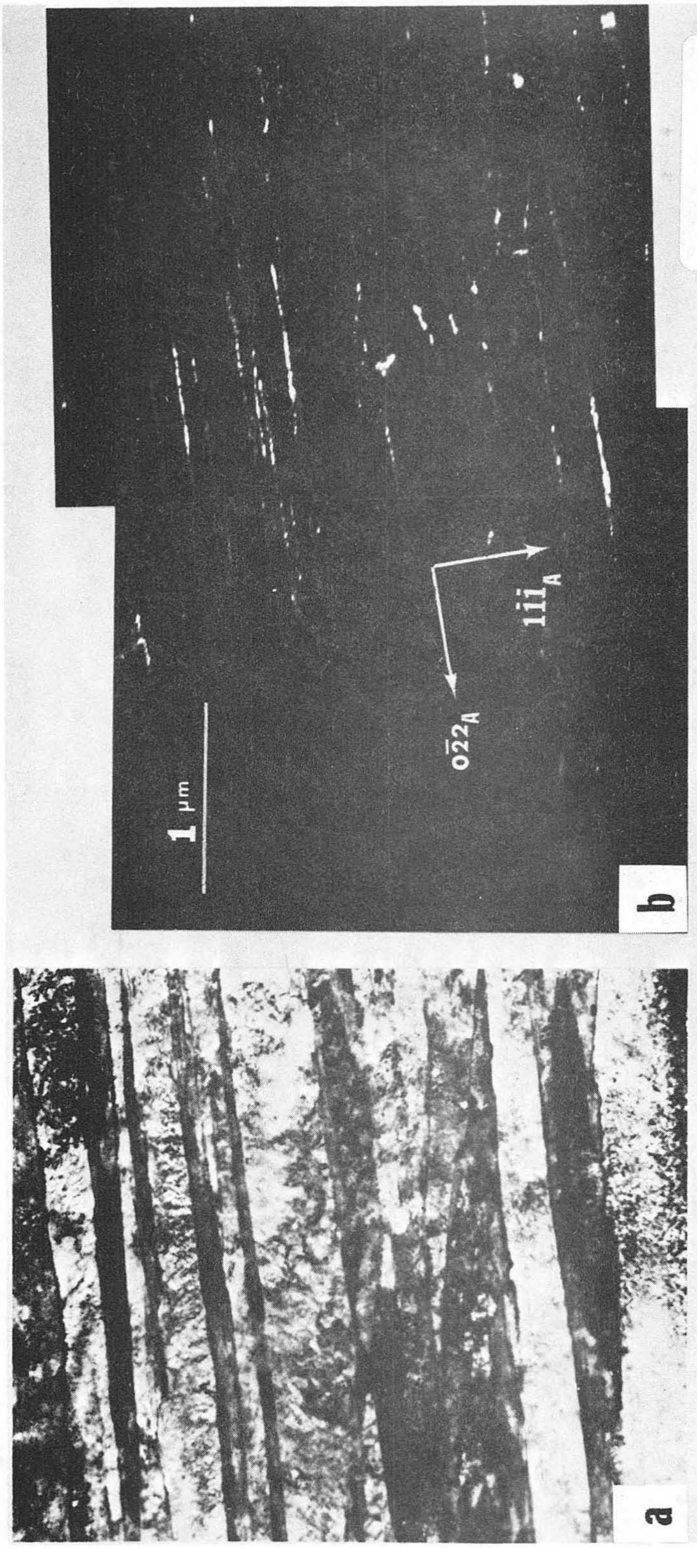

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Fig. 3

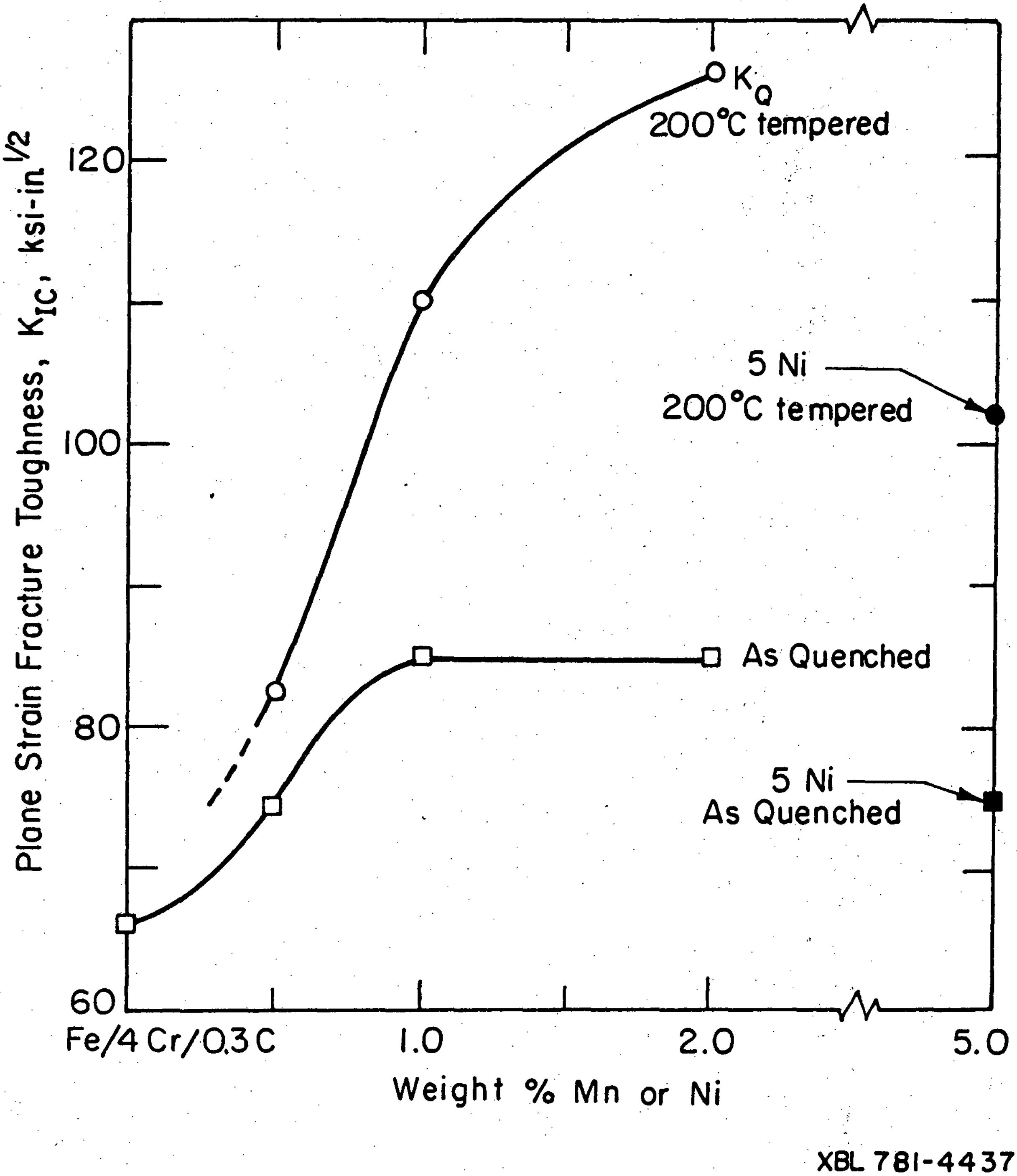

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Fig. 4

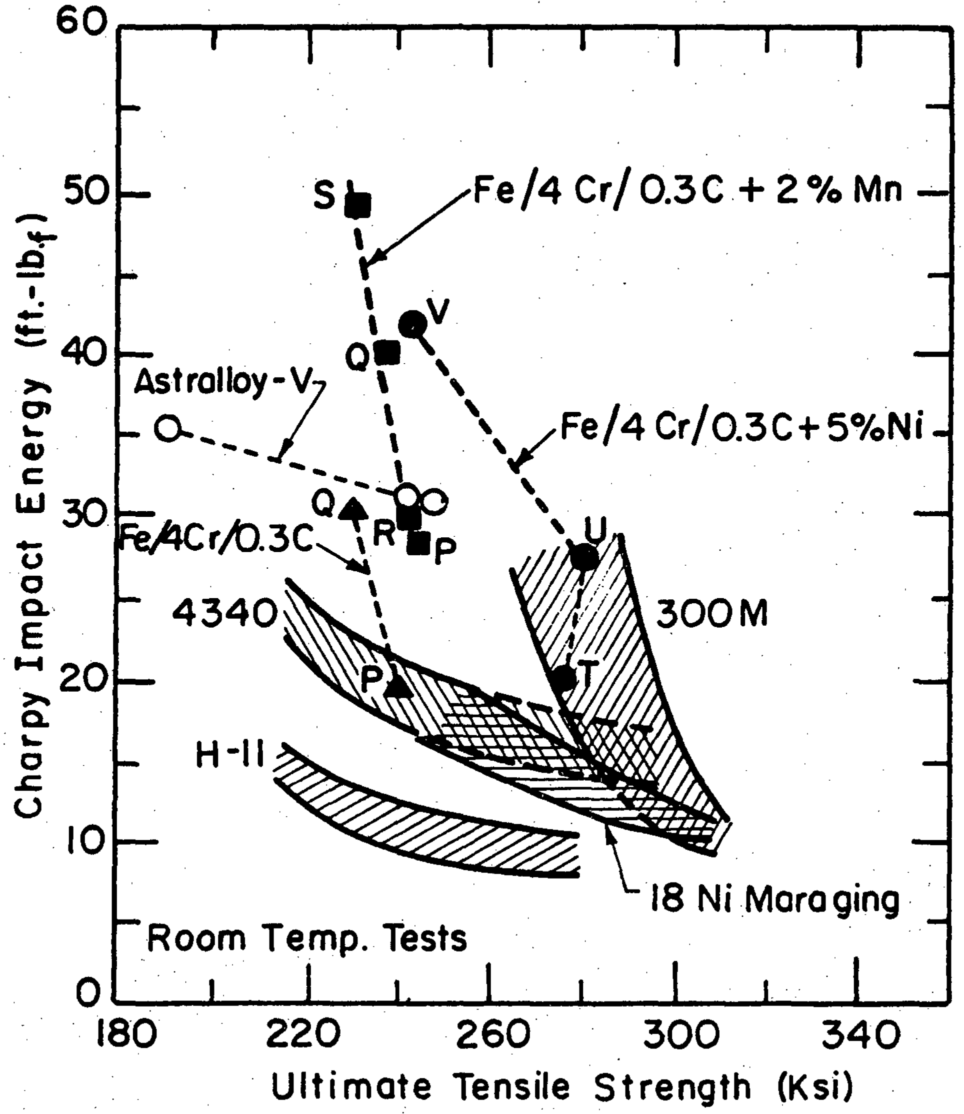

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Fig.5

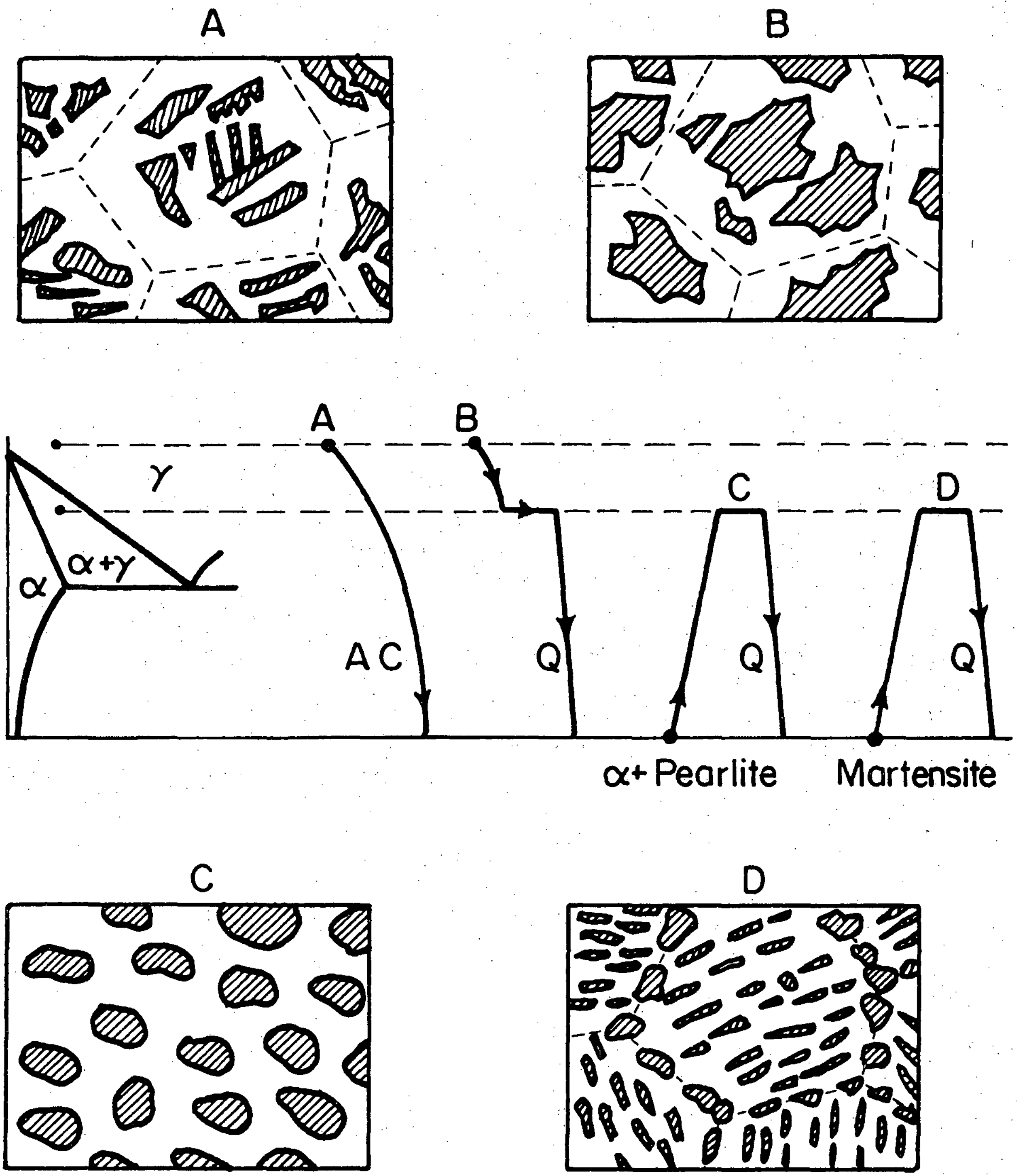

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Fig.6

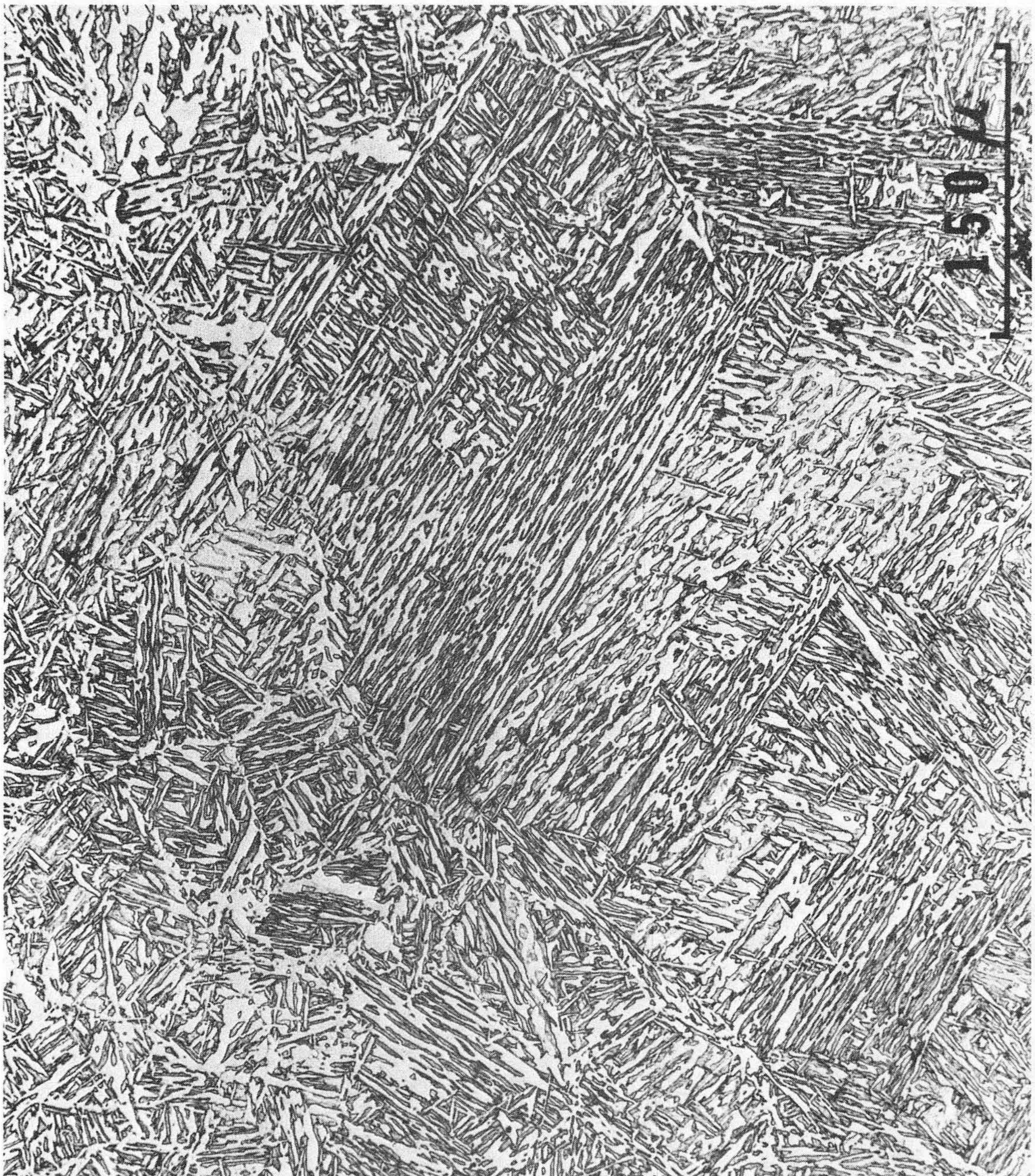

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Fig. 7(a)

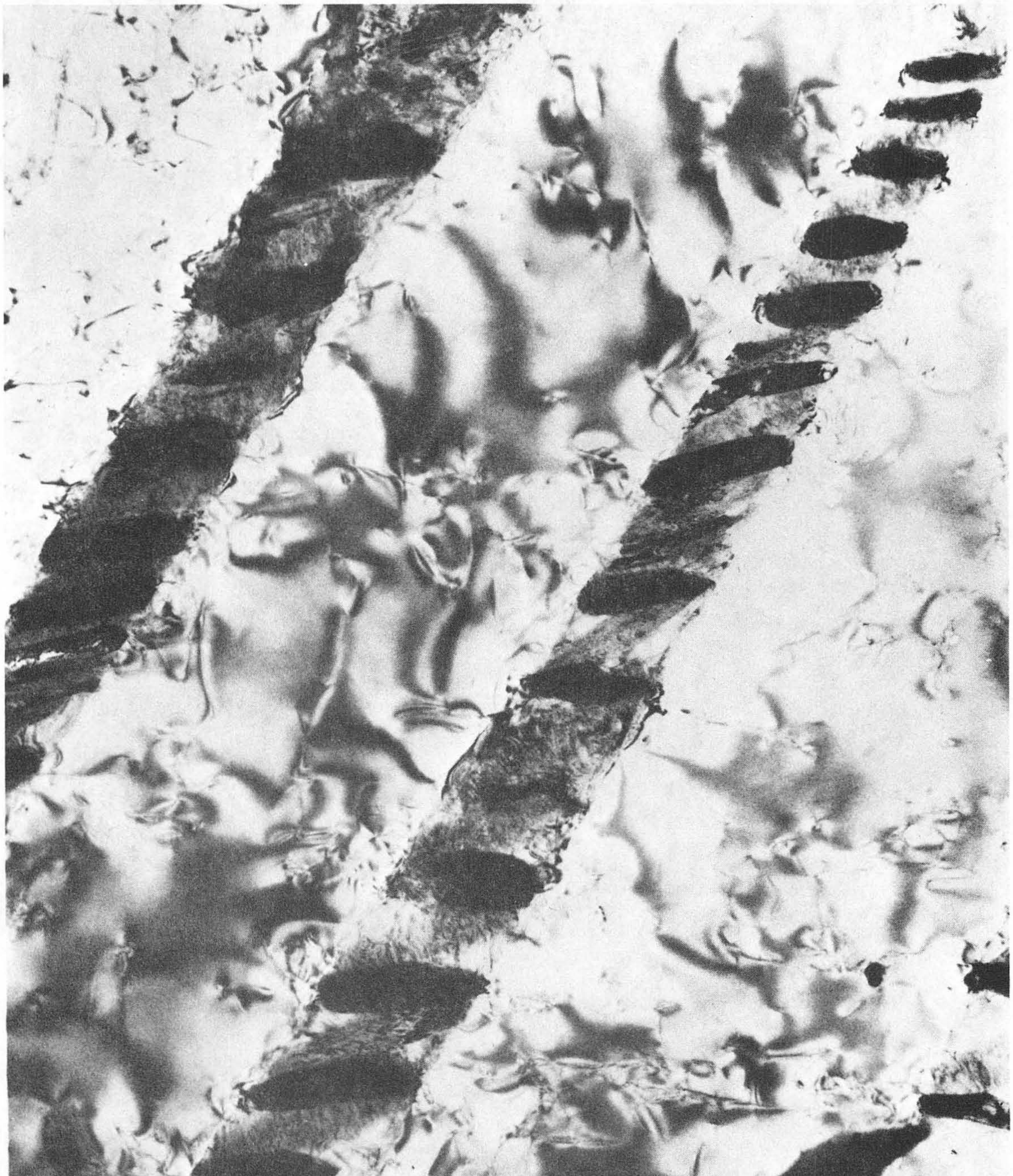

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FIg. 7(b)

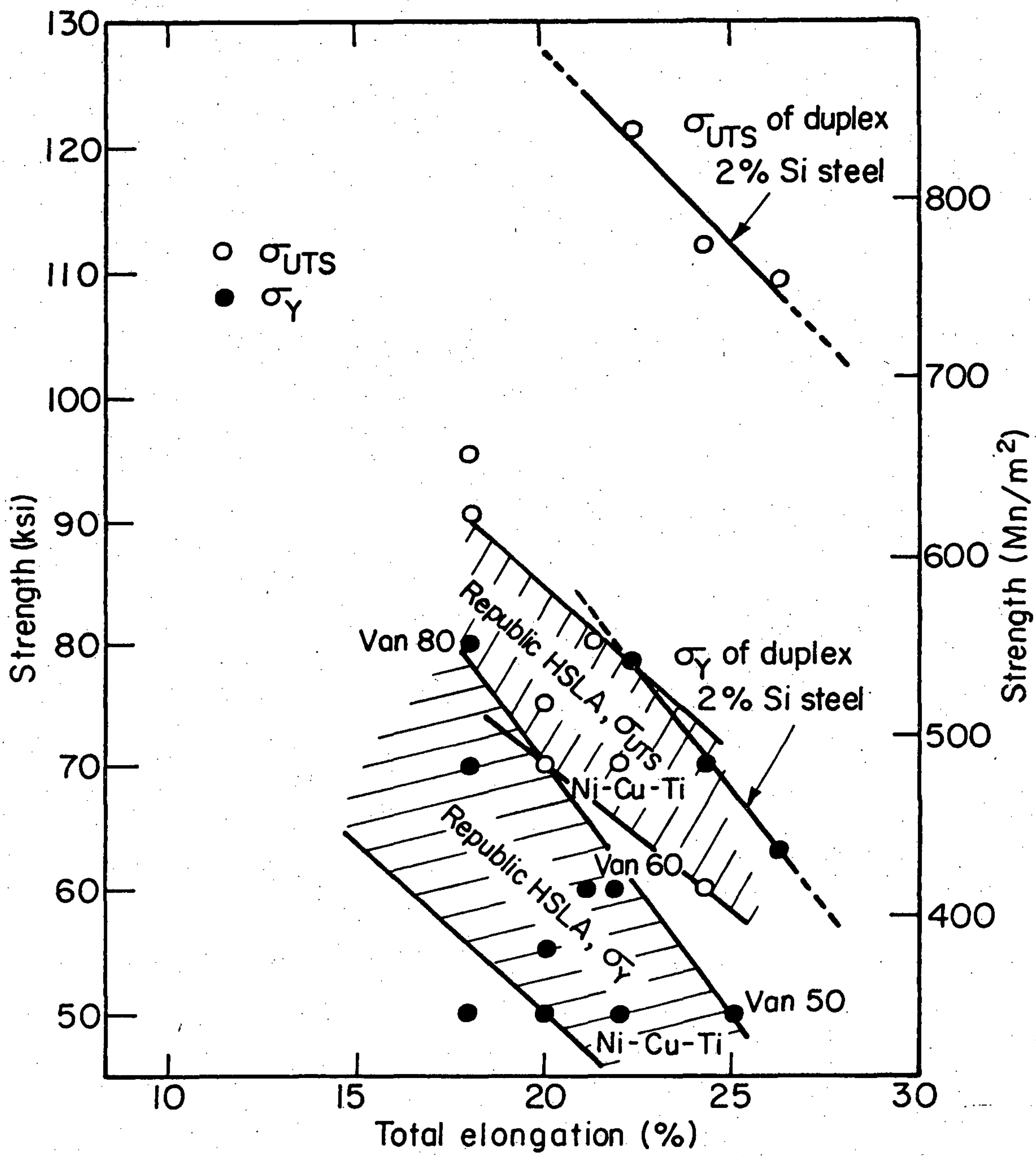

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Fig. 8

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