Title
UNTEMPERED ULTRA HIGH STRENGTH STEELS OP HIGH FRACTURE TOUGHNESS

Author
Zackay, V.F.

Publication Date
1972

Submitted as a Letter to the
Editor of Nature

LBL-478 c.2
Preprint

UNTEMPERED ULTRA HIGH STRENGTH STEELS OF HIGH FRACTURE TOUGHNESS

V. F. Zackay, E. R. Parker, R. D. Goolsby, and W. E. Wood

January 1972

AEC Contract No. W-7405-eng-48

DISCLAIMER

UNTEMPERED ULTRA HIGH STRENGTH STEELS OF HIGH FRACTURE TOUGHNESS

V. F. Zackay, E. R. Parker, R. D. Goolsby, and W. E. Wood

Inorganic Materials Research Division, Lawrence Berkeley Laboratory and Department of Materials Science and Engineering, College of Engineering; University of California, Berkeley, California

The ultra high strength steels currently in use were developed decades ago by trial and error methods. They all have certain undesirable characteristics, such as low fracture toughness at high levels of yield strength. Although many new concepts of alloying and micromechanics of fracture have recently evolved through research, little effort has been made to use this new knowledge to improve existing alloys, or to find new ones with better combinations of properties.

We have recently been engaged in a study of the factors that contribute to notch brittleness in high strength steels. The use of electron microscopy has added significantly to our knowledge of austenite transformation kinetics and morphological features of transformation products. As a consequence, the micromechanics of brittle fracture have become clearer, and we are learning how to avoid undesirable microstructural features that are unresolvable with an optical microscope. An important result of our recent research is that we have learned how to increase the fracture toughness of steels having yield strength in excess of 200,000 psi by as much as 70 percent.

The standard heat treatment for quenched and tempered low alloy steels involves heating to the lower end of the austenite temperature range (to minimize grain size), quenching fast enough to produce martensite, and tempering at a temperature that will optimize mechanical properties. The treatments that we used to improve properties differed in a significant way from commercial practice; the differences are discussed in detail in a later section.

The tensile properties and the fracture toughness of two commercial (A.I.S.I. types 4130 and 4340) steels and a special secondary hardening steel (5% Mo-0.60% Mn-0.30%C) were determined as a function of austenitizing temperature and quenching medium. The variation with austenitizing temperature of the plane strain fracture toughness, K_{Ic}, is shown for the special steel in Fig. 1. All specimens were quenched in iced brine. Austenitizing above about 1100°C increased the fracture toughness by a factor of two. Within the temperature range corresponding to the increase in fracture toughness, there was a concomitant increase in the austenite grain size. A large austenite grain size (long thought to be an undesirable microstructural feature for optimum strength and toughness)is actually beneficial to toughness.

The yield and the tensile strengths appeared to be relatively insensitive to wide variations in austenitizing temperature, as is shown in Table I, but the elongation and reduction in area decreased with increasing austenitizing temperature above about 1100°C. The loss in ductility caused by drastic quenching from high austenitizing temperatures can be recovered in this steel, however, by a low tempering treatment, i.e., below 225°C, without a significant decrease in either strength or toughness.

A similar variation of fracture toughness with austenitizing temperature has been observed in several commercial low alloy medium carbon steels. The influences of austenitizing temperature and quenching medium on A.I.S.I. type 4130 steel is shown in Table II. The more drastic quench (iced brine vs. oil) at the higher austenitizing temperature (1200°C) further enhanced the fracture toughness. The range of austenitizing temperatures recommended in commercial practice is 835-915°C.

The relationship between austenitizing temperature and quenching rate was investigated for a widely used commercial steel (A.I.S.I. type 4340). All specimens were given an initial austenitizing treatment at a temperature of 1200°C and either directly quenched or, alternatively, cooled to 870°C and then quenched into one of three different media--iced brine, water or oil. The resulting values of plane strain fracture toughness are given in Table III.

Several conclusions can be drawn from these experiments. It appears that to achieve high fracture toughness it is neither necessary nor desirable to quench directly from a high austenitizing temperature. A two step quench minimizes the danger of quench cracking and results in about the same fracture toughness as a single quench from the highest austenitizing temperature, as shown in Table III. The higher carbon content of the 4340 steel (compared to the 4130) led to cracking when the steel was quenched from 1200°C. Secondly, it appears that for the more highly alloyed 4340 steel, the austenitizing temperature is more important than quenching rate for optimizing toughness, as shown by the results of the two step treatment reported in Table III. Thirdly, it is apparent that at the low austenitizing temperature employed in commercial practice (870°C), the fracture toughness is about fifty percent lower than that attainable by the two step austenitizing treatment. Finally, in this regard it is of interest that quenching into media other than oil results in quench cracking to a much greater extent when the single austenitizing treatment at 870°C is used than when the two step treatment is employed.

The precedent for the quenching and tempering of steel antedates the Industrial Revolution for, as is well known, the practice of tempering or "drawing" the quenched steel to improve its toughness was familiar to the medieval artisans of Europe and Asia. Modern metallurgists generally assume that martensite in medium carbon as-quenched steel is intrinsically brittle. Many theories have been advanced, largely based upon microstructural considerations, to explain this presumed intrinsic brittleness. However, experiments of the type described above show that untempered medium carbon martensite may be extraordinarily tough as well as strong and hard. Indeed, the strength and toughness of these drastically quenched and untempered low alloy steels (3 to 5 percent total alloying elements) are equaled only by those of the high alloy (about 30 percent total alloying elements) and costly maraging steels.

The initial research effort in our laboratory was directed toward determining the cause of the brittleness of conventionally quenched low alloy steels. Although there are many factors which could contribute to the observed brittleness, our experiments suggest that in low alloy steels certain isothermal decomposition reactions occur which can lead to transformation products that decrease toughness. Mixed microstructures are known to be deliterious to toughness, especially when a minor phase is present as a network in the prior austenite grain boundaries. The effectiveness of a high austenitizing temperature in reducing brittleness is attributed to the fact that grain boundary nucleation of a second phase is retarded when the high energy grain boundaries associated with small grains are eliminated by the grain growth process.

Our research program is directed toward developing a new class of ultra high strength steels having markedly higher fracture toughness than existing steels. This we propose to do through microstructural control dictated by alloy theory, nucleation theory, and concepts of micromechanics of fracture.

The authors gratefully acknowledge the assistance of Mr. Thomas Tom, who cooperated with us in the testing program. This work was done under the auspices of the U. S. Atomic Energy Commission.

V. F. Zackay
E. R. Parker
R. D. Goolsby
W. E. Wood

University of California
Department of Materials Science and Engineering
Hearst Mining Building
Berkeley, California 94720

TABLE I

AUSTENITIZING TEMPERATURE AND TENSILE PROPERTIES
OF A 5%Mo-0.60%Mn-0.30%C STEEL

Austenitizing Temperature, °C	Yield Strength, Ksi	Tensile Strength, Ksi	Elong., % in 1"	Red. of Area %
1255	205	245	7	20
1225	214	261	8	26
1115	210	260	11	32
1060	212	251	12	48
1005	198	244	13	47
895	194	228	13	47

XBL 721-5952

TABLE II

AUSTENITIZING TEMPERATURE, QUENCHING MEDIA AND
FRACTURE TOUGHNESS OF A COMMERCIAL STEEL (A.I.S.I. 4130)

Austenitizing Temperature, °C	Quenching Medium	Fracture Toughness, K_{Ic}, (Ksi-in$^{1/2}$)
1200	iced brine	98.5
1200	oil	83.5
870	oil	58.0

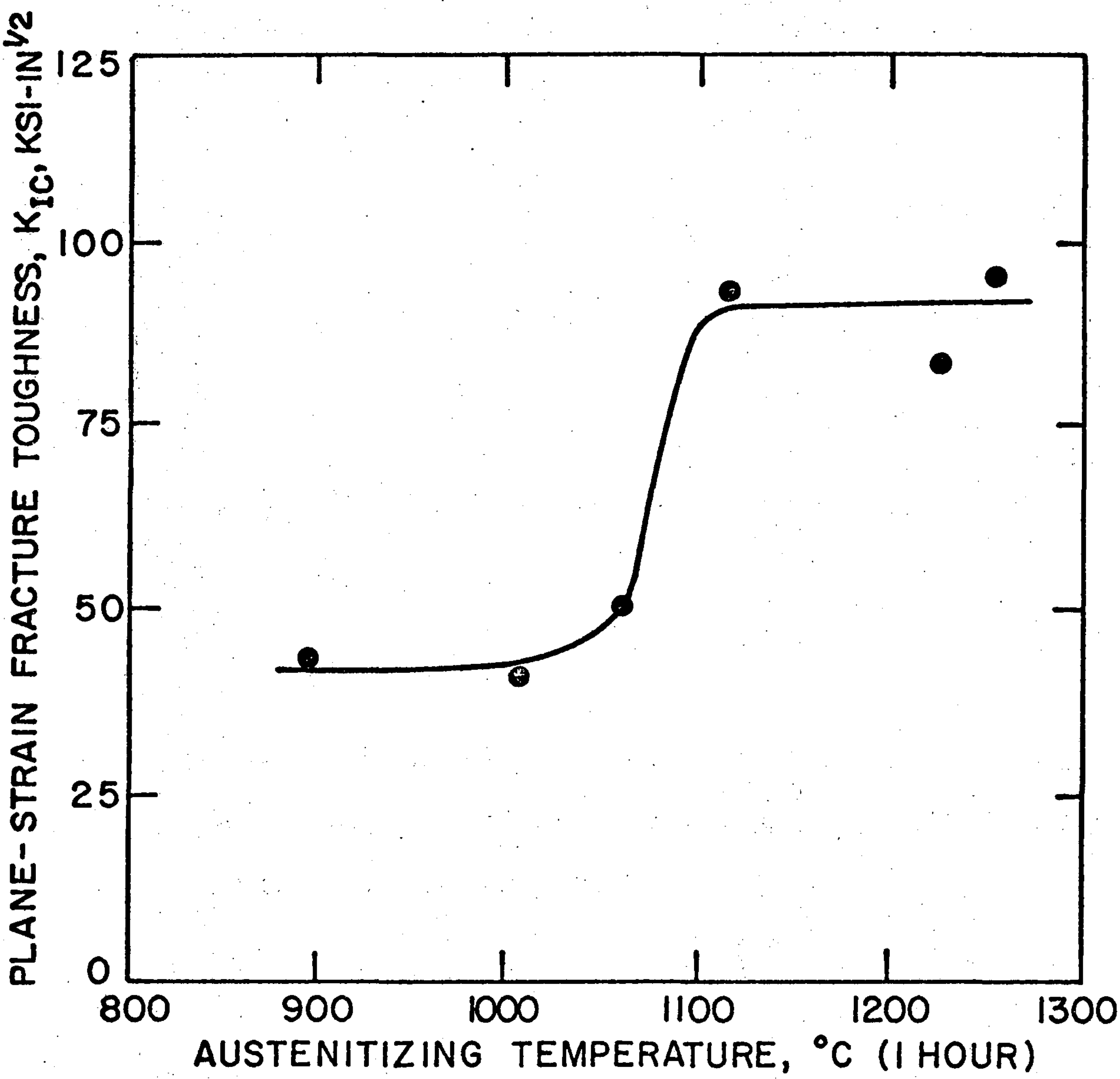
XBL 721-5953

TABLE III

AUSTENITIZING TREATMENTS, QUENCHING MEDIA AND FRACTURE TOUGHNESS OF A COMMERCIAL STEEL (A.I.S.I. 4340)

Austenitizing Temperature, °C (and quenching procedure)	Quenching Medium	Fracture Toughness, K_{Ic}, (Ksi-in$^{1/2}$)
1200, direct quench	iced brine	cracked on quenching
	water	cracked on quenching
	oil	67.3
1200 to 870 and quench	iced brine	62.3
	water	61.1
	oil	63.8
870, direct quench	iced brine	cracked on quenching
	water	cracked on quenching
	oil	40.0

XBL 721-5954



XBL 721-5951A

Fig. 1 Influence of austenitizing temperature on the plane strain fracture toughness, K_{Ic}, of an as-quenched special secondary hardening steel (5% Mo-0.60% Mn-0.30%C).