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To be presented at the 4th International Conference on Strength of Metals and Alloys, Nancy, France, August 30 - September 3, 1976

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April 1976

Prepared for the U. S. Energy Research and Development Administration under Contract W-7405-ENG-48

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IMPROVEMENTS IN STRENGTH AND TOUGHNESS OF EXPERIMENTAL Fe-Cr-C STEELS

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In a previous paper (1) it was shown how simple heat-treatments and control of composition to produce dislocated martensite with interlath films of austenite lead to extremely attractive combinations of high strength and fracture toughness in Fe-4Cr-0.35C steel even without tempering. This paper describes continuing efforts to improve upon this economical, high toughness, ultra-high strength Fe-Cr-C steel through modification of heat-treatment (2) and alloying additions. From a fracture mechanics viewpoint, increasing the strength without a corresponding increase in fracture toughness only results in poor utilization of the available strength of the steel in engineering applications where resistance to the propagation of existing cracks is important. Accordingly, in this investigation the carbon content of all alloys was maintained below 0.35%, and alloy additions of Mn and Ni were employed to achieve desirable microstructural features for hardenability, strength and toughness. Also, since the effects of prior austenitizing conditions on the properties can be considerable, studies of this were a major part of the program.

The procedures for specimen preparation and examination were described elsewhere (1). Slow bend Charpy V-notch tests were performed to obtain "apparent" fracture toughness (K_A) data (3). All the other mechanical tests were carried out according to the relevant ASTM specifications.

INFLUENCE OF AUSTENITIZING TEMPERATURE ON THE BASE Fe-Cr-C ALLOYS

Previous research (4) has shown that increasing the austeni-

tizing temperature from conventional levels at 870°C to 1200°C can lead to increases in the fracture toughness, K_{Ic}, of low alloy steels. However, concurrent with these increases in K_{Ic}, high temperature austenitizing treatments can lead to decreased Charpy impact energies and reduced tensile ductility (3). Test specimens were austenitized at a range of temperatures from 870°C to 1200°C for one hour and quenched in agitated oil. The mechanical properties of the as-quenched steels are shown in Figs. 1-6. It can be seen that although the yield and ultimate strengths are unaffected by austenitizing treatment, the toughness and ductility are markedly altered, as seen previously in 4340 alloy steel (3). The fracture toughness, K_{Ic} is seen to increase steadily with austenitizing temperature up to 1100°C (Fig. 3), although there is no corresponding increase in Charpy impact energy except at 1000°C. The rounded notch slow bend Charpy tests, where an "apparent" fracture toughness at failure (K_A) was measured (Fig. 3), show a steady decrease in critical fracture stress and strain with austenitizing temperature. The latter fact is consistent with a decrease in ductility and true fracture stress (from a tensile test) with austenitizing temperature, as shown in Fig. 5. Both elongation and reduction in area are also generally reduced with austenitizing temperature, although there is evidence of increased ductility from 870°C to 1000°C in the 0.30% steel. Clearly, it is insufficient to characterize the toughness of a material solely in terms of K_{Ic}, since resistance to failure can be dependent upon the geometry of the crack (3).

Electron microscopy investigations revealed that the primary difference in the microstructure (mainly dislocated martensite) was the undissolved carbide (M_7C_3 type) morphology. The carbides were smaller and more widely spaced as the temperature was raised from 870°C to 1200°C. The microstructural aspects will be described in more detail elsewhere. Fractography revealed that all structures failed by dimpled rupture. However, at 870°C there was evidence of extensive quasi-cleavage, whereas at 1200°C intergranular fibrous rupture was observed around re-precipitated chromium sulphides at prior austenite grain boundaries.

It is apparent that increasing the austenitizing temperature from conventional temperatures, 870°C, is beneficial in that solution of carbides reduces the number of nucleation sites for cracks. This leads to increased fracture toughness without reduction in strength. However, austenitizing above 1100°C leads to no further increase in K_{Ic}, and furthermore, maximizes the deterioration in Charpy energy and ductility properties. It is clear that for this steel the optimum combination of properties is obtained by austenitizing between 1000 and 1100°C.

TABLE I

Composition of the Alloys

Alloy	Element w/o				
	Cr	C	Mo	Ni	Fe
A	4.0	0.35	-	-	bal.
B	4.0	0.30	-	-	bal.
C	4.0	0.24	0.54	-	bal.
D	4.0	0.25	1.93	-	bal.
E	3.8	0.27	-	5.0	bal.

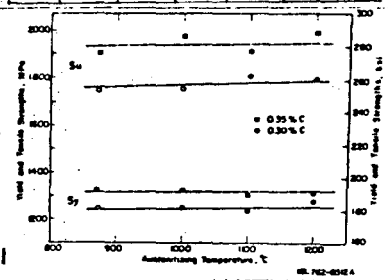

Fig. 1

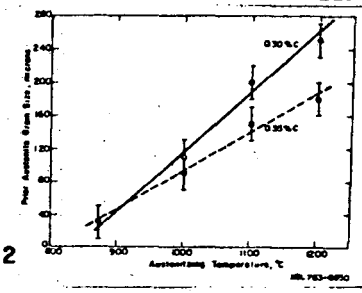

Fig. 2

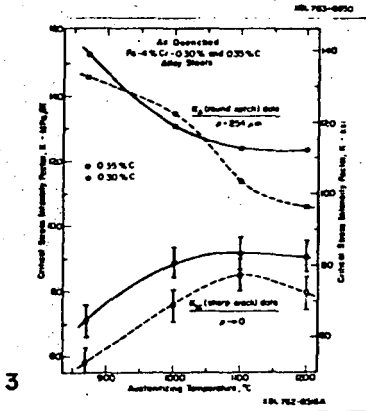

Fig. 3

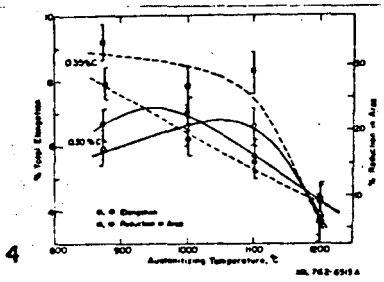

Fig. 4

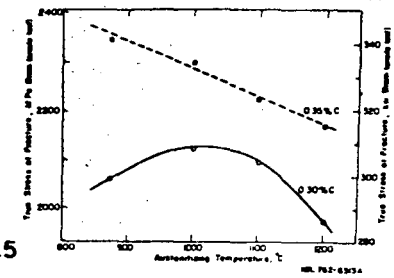

Fig. 5

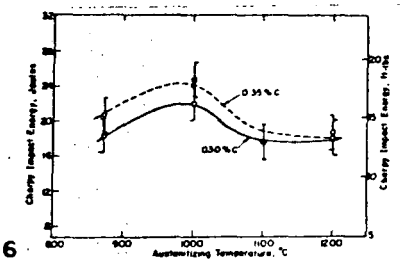

Fig. 6

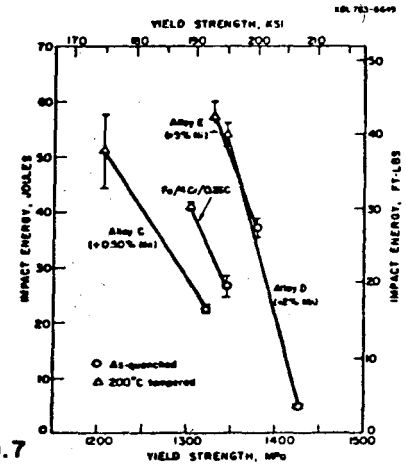

Fig. 7

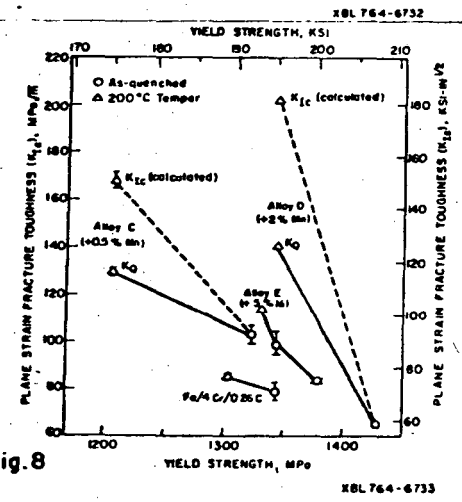

Fig. 8

Figs. 1 through 6: Variation of mechanical properties of ternary Fe/Cr/C alloys with austenitizing temperature.
Figs. 7 and 8: Variation of mechanical properties of a ternary Fe/Cr/C alloy with quaternary alloying.

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INFLUENCE OF QUATERNARY ALLOY ADDITIONS

The main objects of quaternary alloy addition to the basic Fe-4Cr-0.3C steel were to improve the toughness and hardenability of the alloy. Mn and Ni were chosen since both elements are known to lower the ductile-to-brittle transition temperature of steel and to introduce retained austenite in the as-quenched microstructures at room temperature (5). The beneficial effect of retained austenite on toughness of steel has been discussed previously (1,6). It is known that Mn addition to steel improves hardenability and, at higher percentages, promotes twinned substructures (7). A 2% Mn addition is expected to be optimum (7).

Mn and Ni additions to the base alloy resulted in mechanical properties shown in Figs. 7 and 8. Except for the Ni containing alloy (Alloy E), all specimens were quenched into ice water after 1 hr. austenitization at 1100°C. For the Ni bearing alloys double treatments to grain refine the structure were necessary in order to lower the transformation and thermal strains (2). These alloys were held at 200°C (below M_s) for 1 min. following 1100°C austenitizing before quenching to room temperature. Some of the specimens were subsequently grain refined at 870°C (1 hr.) and oil quenched.

Quaternary alloy additions did not significantly alter the yield strength of the base alloy. However, substantial increases in tensile strength were obtained with 2% Mn and 5% Ni additions (175 and 275 MPa respectively). From Fig. 8, it is clear that virtually all additions of Mn and Ni results in superior plane strain fracture toughness values as compared to basic ternary alloy at the same yield strength, especially for the 2% Mn alloy. For some of the tempered specimens, K_{Ic} values were computed from the equivalent energy method (8), using maximum load before failure (Fig. 8). The influence of alloy additions on Charpy impact energy is shown in Fig. 7 from which again it is clear that a 2%Mn addition or a 5%Ni addition to the steel improves the Charpy energy almost 100% at the same yield strength viz., 1340 MPa. Fractographs of Charpy specimens of the as-quenched structures revealed large fractions of quasi-cleavage fracture. With tempering at 200°C, the mechanism changed to predominantly dimpled rupture leading to much increased Charpy impact energies. Details of the metallography will be described elsewhere.

In summary an important result of this work is in the evaluation of toughness with austenitizing temperature. The resistance to fracture of the conventionally (870°C) austenitized structure is greatest ahead of a rounded notch (i.e. in Charpy and K_A tests), whereas it is least ahead of a sharp crack (i.e.

in K_{Ic} test). Therefore, the advantages of increased fracture toughness, K_{Ic}, with increased austenitizing temperature, must be weighed against the deterioration of ductility and Charpy impact energy. However, an optimum austenitizing temperature can be chosen (in the range1000-1100°C), where one achieves a 30-50% increase in fracture toughness, K_{Ic}, with no loss of strength and little reduction in impact energy and ductility.

Moreover, low alloy additions of Mn and Ni can further increase the toughness of the alloy without reduction in strength. This was possible because the strengthening in these quaternary alloys was achieved primarily through solid solution hardening and not from substructural twinning in martensite. The toughness properties obtained for Fe-4Cr-2Mn-0.26C steel are far superior to conventional 4340 and 300-M steels at the 200 ksi (1400 MPa) yield strength level, and yet would be cheaper to produce in large quantities.

This research was supported by the Energy Research and Development Administration through the Materials and Molecular Research Division, Lawrence Berkeley Laboratory. R.O.R. acknowledges the award of a University Miller Fellowship. Daido Steel Corporation kindly provided the steels to our specifications.

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