Interrelations of Microstructure, Mechanical Properties and Fracture Behaviour in a Cr-Mo Steel*

By F. H. SAMUEL**

Synopsis

Investigations have been carried out to determine the effect of structure viz., martensite, bainites and ferrite-carbide aggregates on the tensile and tear properties as well as the nature of fracture in a 0.11%C-1.5%Mn-1.04%Cr-0.25%Mo-0.003%B steel. Both total elongation and uniform elongation vary almost linearly with tensile strength, the ratios of uniform elongation to total elongation being confined to 0.6~0.7. Replacing total elongation by uniform elongation to characterize the high strength-ductility combination is not found to be identical. The toughness (as measured by unit propagation energy) follows a trend almost similar to that of $TS \times El$. Shear and/or microvoid coalescence are the operating modes of fracture and these, in turn, depend on the steel toughness and structure.

I. Introduction

During the last two decades, the market for high-strength tough steels having yield strength in the range 350~770 MNm⁻² has expanded rapidly. In low-carbon manganese steels a minimum 560 MNm⁻² yield strength is achieved with a ferrite-pearlite structure. Above this level the steel should contain bainite and/or temper martensite structure.¹⁾ Molybdenum and boron are very effective in improving the steel hardenability and, hence, enhance the bainite formation even on normalizing.^{2,3)} Chromium, like molybdenum, tends significantly to facilitate the bainite hardenability and promotes the occurrence of austenite bay.⁴⁾ In the present study an alloy is selected to contain 0.11%C-1.5%Mn-0.003%B to which 1 % Cr and 0.25 % Mo were added. The findings of Gerberich *et al.*⁵⁾ show that in such steels a mixed bainitic-martensitic structure would exhibit better toughness than temper martensite structure. The existence of proeutectoid ferrite is not desirable due to its poor hardenability.

The effect of structure on the steel strength and toughness when it contains 0.15 % C and 1.5 % Cr and Mo has been studied by Kamada *et al.*⁶⁾ and Kunitake *et al.*⁷⁾ Another school of thought⁸⁾ suggested using a single parameter, the product of tensile strength and ductility to characterize the combination of strength and ductility as a function of microstructure.

The present investigation determines the effect of martensite, bainites and ferrite-carbide aggregates on the tensile properties, ductilities and toughness in the above mentioned steel and aims to correlate the variation in these parameters with fracture modes.

II. Experimental Procedure

An air-melted Cr-Mo steel (0.11%C-1.5%Mn-

1.04%Cr-0.25%Mo-0.003%B) was received in the form of ingot 80×80×200 mm and hot forged into plates 6 mm thick. Specimens for heat treatment were cut from these plates and austenitized at 1 000 °C for 1 hr prior to either quenching in iced brine, cooling in air (normalizing) or transforming isothermally in molten baths. The quenched as well as normalized steels were subjected to isochronal tempering upto 700 °C.

Tensile tests were performed on shouldered specimens (Hounsfield No. 12 with gauge length 13 mm and diameter 4.5 mm), whereas tear tests were carried out on specimens with dimensions shown in Fig. 1.⁹⁾ All tests were conducted at room temperature using the same strain rate. The strain hardening exponent 'n' was calculated from the relation:

$$\sigma = E\epsilon^n$$

where, σ , ϵ : the true stress and strain, respectively
 K , n : constants.

A scanning electron microscope was used in examining the microstructure of specimens, after polishing and etching in 2 % nital, at 25 kV. Fractured surfaces of tear test specimens were investigated using the same microscope.

III. Results and Discussion

1. Microstructure

Photograph 1(a), shows the microstructure of quenched steel comprising packet martensite as would be expected for this grade of steel. Such packets are generally composed of several laths containing high dislocation densities.¹⁰⁾ Although the martensite packets are retained on tempering at elevated temperatures, *i.e.*, 600 and 700 °C, Photo. 1(b), the lath morphology is broken down into ferrite and carbide.¹¹⁾ This process is associated with great dislocation annihilation and the formation of recovered and/or recrystallized ferrite grains.¹²⁾ The microstructure obtained for normalized steel exhibit typical granular bainite, Photo. 2(a). In this case, as well, the granular bainite structure persists on tempering even at 700 °C, Photo. 2(b), a temperature which represents recrystallization of bainite laths.⁹⁾

An isothermal transformation at 350 °C (a temperature below the M_s) results in mixed packets of martensite and lower bainite microstructure as shown in Photo. 3(a). Increasing the transformation temperature changes the structure to lower bainite at

* Received August 16, 1982. © 1983 ISIJ

** Central Metallurgical Research & Development Institute, National Research Centre, Cairo, Dokki, Egypt.

Fig. 1. Schematic diagram for tear test specimen and load-expansion curve.

Photo. 1. Microstructure showing packet martensite in a) as-quenched, and b) quenched and tempered at 600 °C.

Photo. 2. Microstructure showing granular bainite in a) as-normalized, and b) normalized and tempered at 700 °C.

400 °C, upper bainite at 450 °C and granular bainite at 550 °C (the $B_s \sim 575$ °C). At 625 °C, ferrite grains appear in the microstructure together with carbide colonies distributed in their interiors, Photo. 3(b).

2. Mechanical Properties

Figure 2 illustrates the variation in tensile strength (UTS) as a function of temperature. It is seen that despite the large difference in the initial normalized and quenched strength values, closer values were at-

tained at 700 °C. The isothermally transformed specimens were also found to approach the same strength levels of normalized and tempered steel at 625 °C. Examination of the microstructures reveals the formation of ferrite for the three steels in this range of temperatures. It is noted that bainite granules offer better resistance to softening than packet martensite or isothermal bainites (the fractional drop in UTS is about 0.15 for normalized steel at 700 °C, 0.35 for quenched steel at 700 °C and 0.35 for isothermal steel

at 625 °C). These observations suggest that recovery of granular bainite may take place at early stages of tempering or during the normalizing process.

With regard to conventional quenched and tempered HSLA steels, in the present case the changes in ductility (as measured by total elongation (EL) or uniform elongation (UE)) were found mostly to decrease linearly with UTS (with varying slopes) as shown in Fig. 3(a). At a given strength, however, tempered martensite or tempered bainite has superior ductility as compared to conventional treatment. Figure 3(b) reveals that the ratio of UE to EL is essentially constant for each process and falls in the range 0.6~0.7 for all the three regimes studied. In similar

Photo. 3. Microstructure of the steel isothermally transformed at a) 350 °C, showing mixed packets of martensite and bainite, and b) 625 °C, showing ferrite and carbide aggregates.

Fig. 2. The variation in tensile strength as a function of temperature.*

* In this paper the abbreviations Q + T, N + T and IT will be used to describe quenched and tempered, normalized and tempered and isothermally transformed conditions, respectively. (see Figs. 3, 4 and 6)

Fig. 3(a).
The variation in elongation as a function of tensile strength.

Fig. 3(b). The variation in UE/EL ratio as a function of tensile strength.

Fig. 4. The variation in strain hardening exponent 'n' as a function of true uniform elongation.

Fig. 5.
The variation in $\text{TS} \times \text{EL}$ and $\text{TS} \times \text{UE}$ as a function of temperature.

Fig. 6.
The variation in unit propagation energy as a function of temperature.

3. Fracture Behaviour

Investigations of the fracture behaviour of tear test specimens were focused on the areas representing crack initiation. The mode of fracture for martensite structure is mainly shear. Tempering leads to predomination of microvoids rupture at high temperatures, *i.e.*, 600 and 700 °C. An example is shown in Photo. 4. It is generally accepted that dimple fracture indicates a better toughness and the size of the dimple is directly related to the precipitated particles of second phase.¹⁷⁾ In Photo. 4, the dimples are in the order of 2~5 μm , whereas transmission electron microscopy reveals that the cementite particles precipitated at 700 °C are in the range of 80~100 Å. Thus it is difficult to correlate the dimple size with the particle size. The normalized steel fractured through

Photo. 4. Fractograph showing microvoid coalescence as predominant mode of rupture in quenched and tempered (at 600 °C) steel.

Photo. 5. Fractograph showing a) shallow dimples in normalized steel, and b) coarse dimples in normalized and tempered (at 700 °C) steel.

formation of shallow dimples (10~20 μm), Photo. 5(a). On tempering, the dimples appear much deeper (Photo. 5(b)) than in the case of tempered martensite (Photo. 4), though both achieved equivalent toughness levels. The present results suggest that the

(a) 350 °C showing secondary crack with quasi-cleavage facets
(b) 400 °C showing mixed shear and dimple rupture
(c) 550 °C showing dimple rupture
(d) 625 °C showing dimple rupture

Photo. 6. Fractograph of isothermally transformed steel.

steel plasticity may have a significant role on the dimple size. Since the granules or islands in normalized structure constitute a large number of bainite laths,⁹⁾ they are more easily deformed and are not, therefore, expected to crack. Thus the voids are likely to nucleate at the massive ferrite/bainite granule interfaces. This mechanism, however, is common in fine fibrous and fine globular dual-phase structure.¹⁸⁾

In Photo. 6(a) is exhibited the fracture surface of steel isothermally transformed at 350 °C. As seen, several transcrystalline cracks appear. It is worth recalling that toughness (see Fig. 6) associates with an increase in proportion of voids as is evident from Photo. 6(b) for lower bainite and in Photo. 6(c) for granular bainite at 550 °C. Transformation at 625 °C reveals coarse microvoids, Photo. 6(d), and the voids are so deep that their bottoms can not be photographed even at high magnifications. Thus it seems reasonable to assume that beyond a certain size of the voids, the toughness is decreased.

IV. Summary and Conclusions

(1) Martensite is the product of quenching, whereas normalizing process is sufficient to induce bainite reaction. Both the martensite packets and bainite granules are retained on tempering at elevated temperatures, *i.e.*, 600 and 700 °C. Isothermal transformation results in mixed martensite and bainites at 350 °C, lower bainite at 400 °C, upper bainite at 450 °C, granular bainite at 550 °C and polygonal ferrite at 625 °C.

(2) The normalized structure offers higher resistance to softening on tempering than martensite or isothermal bainites. Both total elongation and uniform elongation seem to vary linearly with strength. The uniform elongation to total elongation ratios are in the range 0.6~0.7. Although the strain hardening exponent changes linearly with the true uniform elongation for martensite and isothermal bainites, the slope is unity only for normalized steel. There is a marked difference in using TS×EL or TS×UE in determining the strength-ductility relation. The toughness seems to change in a similar trend to the TS×EL parameter as a function of temperature.

(3) The fracture mode of martensite is chiefly shear which changes into microvoids coalescence rupture on tempering at high temperatures. The void nucleation and coalescence are the main fracture mechanism for granular bainite. Lower bainite fractures by shear whereas dimples and shear operate together for upper bainite and complete dimple rupture is observed for ferrite-carbide structure.

Acknowledgements

The author wishes to express his sincere thanks to Professor A. A. Abdul Azim and Dr. A. A. Ramadan, Central Metallurgical Research and Development Institute, for their helpful discussion and comments on the manuscript.

REFERENCES

- 1) P. L. Manganon: *Metall. Trans.*, **7** (1976), 1389.
- 2) K. J. Irvine and F. B. Pickering: *JISI*, **201** (1963), 518.
- 3) K. J. Irvine, F. B. Pickering, W. C. Heselwood and M. Atkins: *JISI*, **186** (1957), 54.
- 4) V. F. Zackay and W. M. Justusson: *Iron Steel Inst. Spec. Rep.*, (1962), No. 126, 14.
- 5) W. W. Gerberich *et al.*: *ASTM Spec. Tech. Publ.*, **370** (1965), 154.
- 6) A. Kamada, N. Koshizuka and T. Funakoshi: *Trans. ISIJ*, **18** (1978), 16.
- 7) T. Kunitake, F. Terasaki, Y. Ohmori and H. Ohtani: *Sumitomo Research*, **8** (1972), 647.
- 8) K. Araki, Y. Takada and N. Nakaoku: *Trans. ISIJ*, **17** (1977), 710.
- 9) F. H. Samuel and D. S. Sarma: *Met. Sci.*, **14** (1980), 101.
- 10) F. H. Samuel: Ph.D. Thesis, Banaras Hindu University, (1979).
- 11) S. K. Sharma, F. H. Samuel and D. S. Sarma: *Steel India*, **1** (1979), 7.
- 12) K. Onel and J. Nutting: *Met. Sci.*, **15** (1981), 89.
- 13) R. G. Davies: *Met. Trans.*, **9** (1978), 671.
- 14) J. Morrow and G. Tither: *J. Metals*, **30** (1978), 16.
- 15) A. R. Marder: *Met. Trans.*, **13** (1982), 85.
- 16) F. H. Samuel and A. A. Hussein: 2nd Conf. on Mechanical Design and Production, Cairo University, Cairo, December, 1982.
- 17) *Metals Handbook*, 8th ed., IX, ASM, Ohio, (1974).
- 18) N. J. Kim and G. Thomas: *Met. Trans.*, **12** (1981), 483.