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The influence of superhardening and alloy modification on the reversible temper-embrittlement behaviour of low-alloy steel

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SYNOPSIS

Superhardening is a new development by which a substantial increase in hardenability above the normal can be achieved in low-alloy steels. This paper concerns the reversible temper-embrittlement behaviour of steels with a superhardenability characteristic. Steels of type BS 530A40 with manganese modifications varying from 0,72 to 1,27 per cent in the superhardenable and conventional condition were compared. It was concluded that superhardenability in itself does not affect the susceptibility of a particular steel to temper embrittlement. However, an increase in manganese content, which was intended to increase the base hardenability of the steel, caused serious deterioration of the temper-embrittlement properties. As the use of manganese, chromium, and nickel to increase base hardenability results in an increase in susceptibility to temper embrittlement, it is suggested that this effect should be countered by the addition of 0,2 to 0,3 per cent molybdenum.

SAMEVATTING

Superverhardbaarheid is 'n nuwe ontwikkeling waardeur aansienlike verbetering in verhardbaarheid bo die normale in lae legeringstale verkry kan word. In hierdie referaat word die effek van superverhardbaarheidseienskappe op die temperbrosheidsgeneigdheid van staal ondersoek. Staal tipe BS 530A40 met wisselende mangaaninhoud van 0,72 tot 1,27 persent en in die superverhardbare en die konvensionele toestand is gebruik. Dit is gevind dat superverhardbaarheid as sulks nie die geneigdheid tot temperbrosheid affekteer nie. Die verhoging in mangaaninhoud met die doel om die basisverhardbaarheid van die staal te verhoog, het egter 'n ernstige nadelige effek op geneigdheid tot temperbrosheid. Aangesien die gebruik van mangaan, chromium, en nickel om die basisverhardbaarheid te verhoog, veroorsaak dat vatbaarheid vir temperbrosheid toeneem, word dit voorgestel dat hierdie effek teëgewerk word deur toevoeging van 0,2 tot 0,3 persent molibdeen.

Introduction

A substantial increase in hardenability above the conventional base hardenability of low-alloy steels can be achieved by superhardening treatment, which requires that the steel melt should be superheated to at least 1650 °C and also that the aluminium content should be a minimum of 0,05 per cent.

Original work in this field was done by Brown and James[1], who reported a substantial increase in the hardenability of BS 150M36 (EN 15) steel. This effect was studied in more detail by Mostert and Van Rooyen[2], whose investigations included steel types of higher base hardenability such as BS 530A40 (EN 18D). They modified the composition of these steels to higher manganese contents (up to 2,55 per cent manganese) in order to increase the base hardenability. They concluded that, in these steels, substantial increases in hardenability are achieved by such superhardening treatment, and that an increase in hardenability due to superhardening treatment is much more pronounced in steels of higher alloy content (higher base hardenability) than in leaner-alloyed steels. A summary of their results is shown in Fig. 1. They also concluded that the magnitude of the superhardening effect is primarily dependent on the base hardenability of the steel, and not on the precise chemical composition. This suggests that all low-alloy steels should respond to superhardening treatment, and that expensive alloying elements can be exchanged for cheaper ones.

The practical advantages of superhardening treatment from the points of view of savings in alloy cost and the conservation of strategic alloying elements are obvious. Mostert and Van Rooyen indicated that superhardenable modified BS 530A40 (EN 18D) with the manganese content increased to 1,52 per cent will have hardenability characteristics similar to those of the expensive, highly alloyed BS 830M31 (EN 27) grade. The total cost of alloying element in modified BS 530A40 is R44 per ton of steel, as opposed to R300 per ton for BS 830M31.

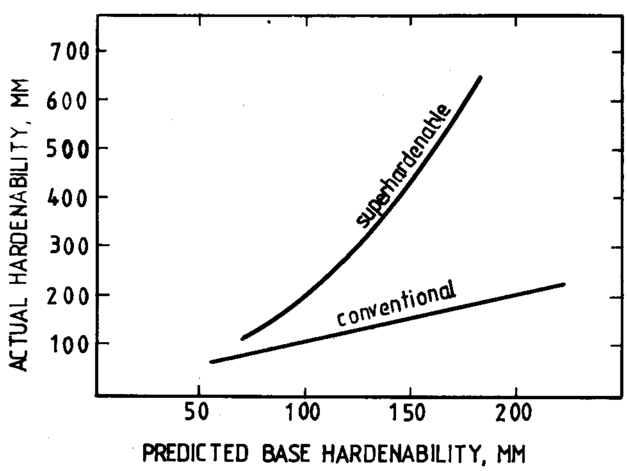

Fig. 1—The hardenability of superhardenable and conventional casts[2]

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The commercial application of a superhardening treatment depends not only on its beneficial influence on hardenability, but also on its effect on mechanical properties (particularly impact properties and fracture toughness, strength properties, and susceptibility to reversible temper embrittlement). For example, it can be expected that the above-mentioned increase in manganese content and possible omission of expensive alloying elements like molybdenum will have an adverse effect on the impact properties and on the susceptibility to temper embrittlement. The present paper deals with the effect of superhardening treatments on the susceptibility to reversible temper embrittlement.

Reversible Temper Embrittlement

Reversible temper embrittlement is a phenomenon that occurs in commercial-grade alloy steels as a result of prolonged heating in the temperature range 375 to 575 °C or slow cooling through that range. It occurs only if the steel contains minute quantities of the impurity elements antimony, tin, phosphorus, or arsenic. However, all commercial-grade steels contain one or more of these elements.

When compared with the unembrittled state, the phenomenon is characterized by an increase in the ductile–brittle transition temperature (DBTT) or the fracture appearance transition temperature (FATT) as determined by the Charpy impact test. The shift in transition temperature (△DBTT or △FATT) can be used as a measure to express the susceptibility of a particular steel to temper embrittlement[3]. An acceptable heat-treatment practice for the evaluation of susceptibility to temper embrittlement involves hardening by quenching, followed by tempering at a temperature above the upper susceptibility range, e.g. 650 °C. After cooling to room temperature, the specimens are embrittled by aging for prolonged periods at a suitable temperature within the susceptibility range[3] (Fig. 2).

The degree and rate of temper embrittlement are appreciably affected by the alloy composition of a susceptible steel[4,5]. Although the carbon content has no drastic effect, the presence of elements like silicon, manganese, nickel, and chromium increases the susceptibility notably. Furthermore, a combination of chromium and nickel always leads to greater susceptibility than that achieved by these elements individually, while a combination of manganese and chromium is even worse. Some alloying elements, namely molybdenum, tungsten, titanium, and lanthanum, are effective inhibitors of temper embrittlement, and thus also counteract the adverse effects of elements like silicon, manganese, nickel, and chromium. Molybdenum in concentrations of 0,2 to 0,6 per cent is most commonly employed as an alloying element in steels to effectively inhibit temper embrittlement.

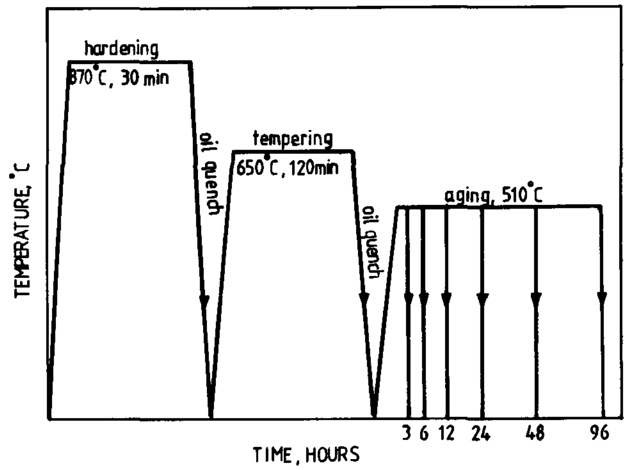

Fig. 2—The heat-treatment cycle for temper embrittlement

The mechanism of reversible temper embrittlement is associated with changes in austenite grain-boundary concentrations of the alloying elements, which occur during aging. Also, it is commonly accepted that an increase in hardenability is due to retardation of ferrite nucleation at the austenite grain boundaries. For these reasons, it is important that the effect of superhardening treatment on the susceptibility to temper embrittlement should also be investigated. From the abovementioned; it is clear that the modification of alloy composition in superhardenable steels could also have an effect on the susceptibility to temper embrittlement.

Experimental

Four casts of 10 kg each were prepared from 530 A40 (EN18D) stock in a vacuum-induction furnace. In three casts, the manganese content was modified to higher values. The final compositions are shown in Table I. Casts A, B, and D were melted in the conventional way (at 1550 °C), while cast C was given a superhardening treatment by melting at 1650 °C and higher aluminium additions. After initial hot forging of the ingots, one standard Jominy bar was machined from each cast, and the remainder were forged to 12 mm square bars, from which standard Charpy specimens were machined (notches were machined after the final heat treatment).

In order to embrittle the Charpy specimens, the heat-

TABLE I
CHEMICAL COMPOSITION OF EXPERIMENTAL STEEL CASTS
(in percentages)

Cast	C	Mn	P	S	Si	Ni	Cu	Cr	Mo	V	Al	Sn	As
A	0,34	1,27	0,026	0,036	0,29	0,15	0,16	0,96	0,06	0,04	0,02	0,026	0,011
B	0,38	1,09	0,021	0,030	0,25	0,21	0,15	0,89	0,09	0,04	0,02	0,026	0,011
C*	0,38	1,20	0,022	0,028	0,26	0,15	0,16	0,96	0,06	0,04	0,09	0,026	0,011
D	0,46	0,72	0,021	0,029	0,26	0,14	0,15	0,97	0,05	0,04	0,02	0,026	0,011

* Superhardenable cast

treatment cycle as shown in Fig. 2 was followed. The effectiveness of the hardening process was checked by hardness measurement of each specimen directly after quenching. The Vickers hardness values were in the range 612 ± 12, which indicate complete hardening. Similarly, after tempering, the hardness of each specimen was checked. The final Vickers hardness values were in the range 295 ± 10. As variations in hardness have an additional effect on the FATT, it is imperative that the final hardness range should be as close as possible.

In the determination of the FATT, Charpy tests were performed according to the standard specifications of ASTM A370 and E23. The testing temperatures ranged from −90 °C to +120 °C. At least six Charpy specimens were used in the determination of each FATT.

Results

The results of the Jominy tests are shown in Fig. 3. In comparison with the Jominy curves for the conventional melts (A and B), the flat Jominy curve for sample C indicates that the superhardening treatment was effective.

The results of the temper-embrittlement experiments are shown in Figs. 4 and 5. In Fig. 4 the variation in the FATT as a function of the aging (embrittling) time of the different samples is compared. In all the tests, there were drastic increases in FATT during aging, from which it is deduced that all these steel compositions are highly susceptible to temper embrittlement. Owing to the limited number of samples available for cast A, evaluations could not be made over the full range of aging times. Consequently, the broken lines on Figs. 4 and 5 indicate only approximate behaviour.

The shifts in △FATT as a result of aging are compared in Fig. 5, which shows that, after aging for 96 hours, sample D (lowest percentage manganese) is least susceptible (△FATT = 79 °C), and that sample A (highest percentage manganese) is most susceptible to temper embrittlement (△FATT =≈ 134 °C). The curve for the superhardenable

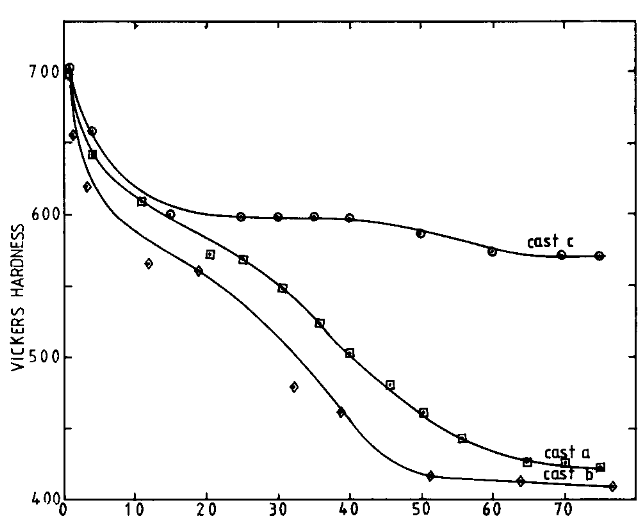

Fig. 3—Jominy test curves for casts a and b (conventional) and cast c (superhardenable)

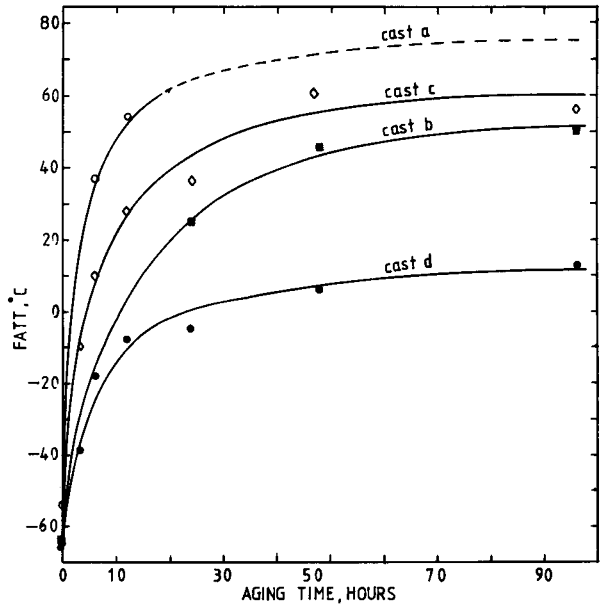

Fig. 4—Variation of FATT as a function of aging time at 510 °C for 530A40 type steel. Cast c (1,20% Mn) was superhardenable, and casts a (1,27% Mn), b (1,09% Mn), and d (0,72% Mn) were cast in the conventional way

sample (C), which had an intermediate manganese content, also lies at an intermediate position.

For comparison, curve E is included in Fig. 5. It shows the results of work done previously[6] on steel of the same composition as that of sample D and made from the same stock material but with a molybdenum addition of 0,28 per cent. It clearly illustrates the beneficial effect of molybdenum in lowering the susceptibility to temper embrittlement.

Discussion

The results shown in Figs. 4 and 5 indicate that the difference in susceptibility to temper embrittlement observed in

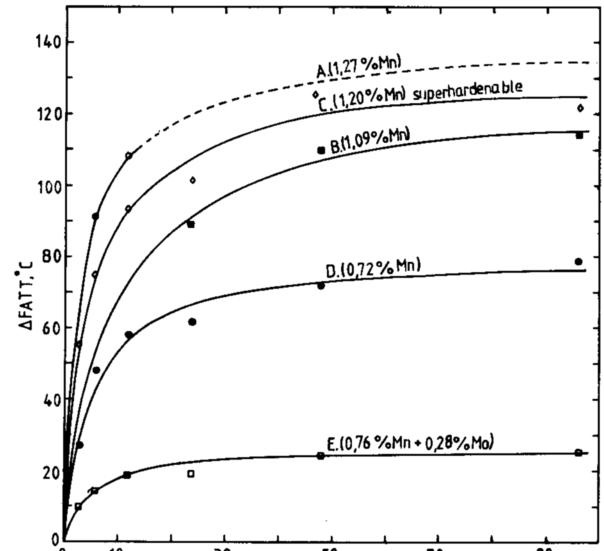

Fig. 5—Shift of △FATT as a function of aging time at 510 °C for 530A40 type steel

the samples investigated is primarily due to variations in manganese content. The sharp increase in susceptibility to temper embrittlement with increasing manganese content is shown in Fig. 6, in which the experimental points were obtained from the results given in Fig. 5. The positions of the experimental points for superhardenable steel (C) show no meaningful deviation from the curves in Fig. 6, indicating that the manganese content of the steel, rather than superhardenability, is responsible for the differences in the susceptibility observed.

As mentioned earlier, Mostert and Van Rooyen employed modified BS 530A40 steel with manganese contents of up to 2,55 per cent to increase the base hardenability of superhardening steel. Although this modification had a very favourable effect on the superhardenability, the adverse effect of the increased manganese content on the temper-embrittlement behaviour would be unacceptable. However, by the addition of molybdenum with a lower manganese content, an increase in base hardenability, as well as an effective retardation of temper embrittlement, would be achieved. The calculated base hardenability according to Grossman[7] of one of the compositions investigated by Mostert and Van Rooyen (modified BS 530A40 with 1,52 per cent manganese) works out as 130 mm ideal critical diameter. The same base hardenability can, however, be achieved if the manganese content of the steel is left at the normal 0,7 per cent and 0,3 per cent molybdenum is added. This modification will not only secure superior resistance to temper embrittlement but also ensure excellent superhardenability response. Although somewhat more expensive than high-manganese steel, this steel will still cost substantially less than conventionally treated highly alloyed steels of comparable hardenability.

Conclusions

This study indicates that superhardening treatment itself does not affect the susceptibility of a particular low-alloy steel to temper embrittlement. However, modification of the steel composition by the addition of certain alloys like manganese in order to increase the base hardenability of the steel has a harmful effect on the temper-embrittlement properties. The results indicate that an increase in the manganese content of from 0,72 to 1,27 per cent in 530A40 steel results in a substantial deterioration of resistance to temper embrittlement.

It is suggested that, when steels of higher base hardenability are required, this should be achieved by the addition of molybdenum or by the use of a standard molybdenum-bearing steel. Molybdenum is effective not only in increasing hardenability but also in inhibiting temper embrittlement. Also, the use of manganese, nickel, or chromium to increase the base hardenability, which results in an increase in susceptibility to temper embrittlement, can be effectively countered by the addition of 0,2 to 0,3 per cent molybdenum.

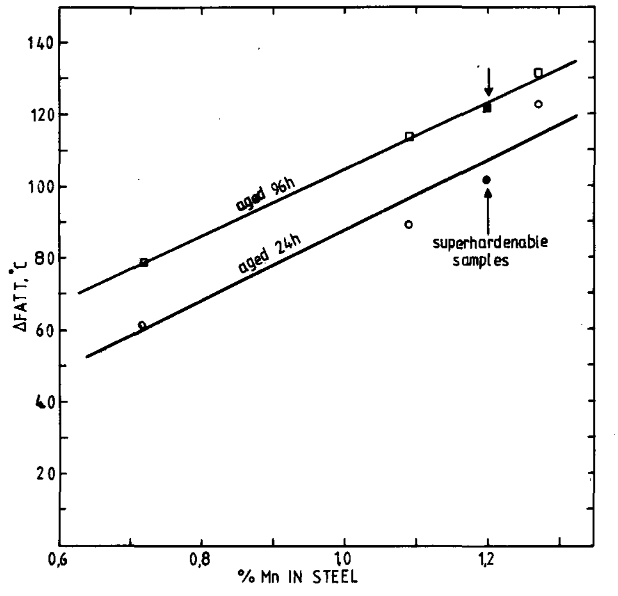

Fig. 6—Shift in ΔFATT as a function of manganese content in 530A40 type steel

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