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Deformation Behaviour Study of Microalloyed Steel by Magnetic Hysteresis Techniques

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ABSTRACT

The magnetic properties of heat-treated, Cu containing, high strength low alloy (HSLA-100) steel and the variations of the magnetic properties during tensile deformation were studied. For samples aged at temperatures below 775 K, precipitation of nanosized coherent Cu particles occurred, causing an increase in hardness but a decrease in coercivity. For higher aging temperatures, the Cu precipitates coarsened and then were able to pin domain walls. As a result magnetic coercivity increased. During tensile deformation of selected heat treated samples, interaction of dislocations with the coherent and incoherent Cu precipitates influenced the magnetic properties. Systematic variation of coercivity with plastic strain was found for brittle and ductile types of fracture of the materials.

INTRODUCTION

In recent years, magnetic evaluation methodologies for the characterisation of engineering components are gaining importance due to their effective correlation with the microstructural and mechanical properties. Amongst different materials for such components, HSLA-100 is considered as a potential microalloyed steel. The unique combinations of high strength coupled with high toughness and corrosion resistance make HSLA-100 steel prospective structural material for naval and other critical engineering applications. In typical naval applications like submarine hulls the structure is prone to deformations arising from dynamic loading. Since the steel has a very low carbon content (≤ 0.06 wt%) to improve weldability, other alloying elements are added to increase strength and impact properties.[1,2] Addition of Mo, Cr, Ni increases hardenability, Cu in the steel increases strength through formation of fine precipitates of copper during tempering and increases weathering resistance. Besides contributing to the strengthening mechanisms, copper also lowers the martensite / bainite transformation temperature and retards recovery and recrystallisation of as-quenched steel.

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As this HSLA-100 steel contains low alloying elements, its magnetic properties are expected to be good enough for soft magnetic application where high strength is required. In this paper the magnetic property of different heat-treated HSLA-100 steel has been studied. The magnetic properties during deformation of this steel have also been studied to explore the feasibility of the technique to evaluate the deformation behaviour by non-destructive way.

EXPERIMENTAL

In the present investigation HSLA-100 steel containing 1.6 wt % Cu and other major alloying elements (in wt%: C: 0.04%, Ni: 3.35%, Mn: 0.95%, Cr: 0.60% Mo: 0.60%, Si: 0.30%, P: 0.02%, Fe: balance) were used. The specimens were austenitized for one hour at 1183 K followed by water quenching. The quenched specimens were aged at different temperatures ranging from 675 K to 975 K for one hour then air-cooled to room temperature. induction (B). Coercivity (Hc) and Initial permeability (μi) are indicated in Figure 1. Tensile specimens were prepared as per ASTM standard and an Instron (10T capacity) universal testing machine was used to study the deformation behaviour. Mechanical properties (YS, UTS, etc) at slow strain rate (0.00012 mm/sec) with a cross-head speed of 0.003 mm/sec were determined. The mechanical hardness and ultimate tensile strength (UTS) of the water quenched and aged samples are shown in Table 1. Magnetic hysteresis loops were measured under a quasi-dc (50 m Hz) magnetizing field using a surface probe. A typical hysteresis loop with different magnetic parameters is shown schematically in Figure 1. The microstructures of aged samples and fractography was observed using Scanning electron microscopy. Transmission electron microscopy was done to identify nanosized Cu-precipitation.

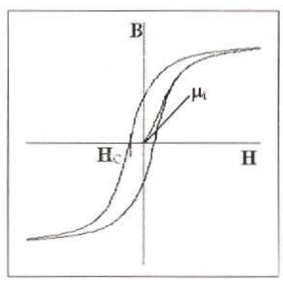


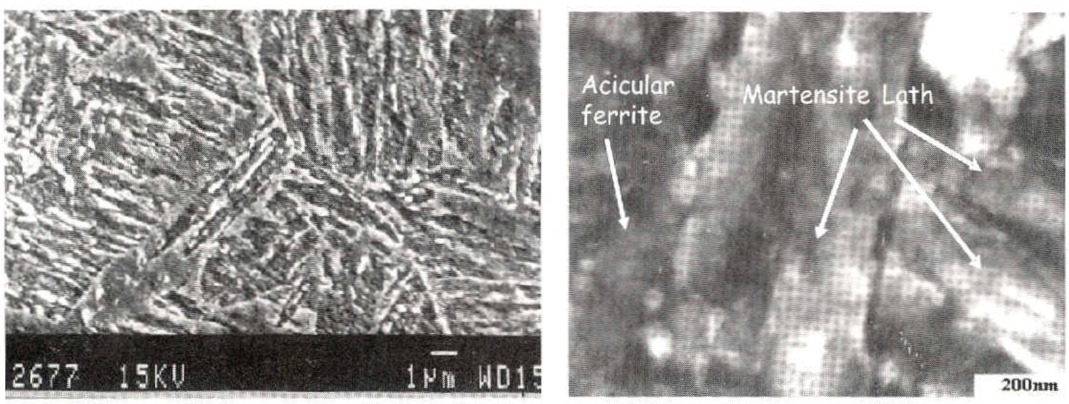
Fig. 1 Magnetic Hysteresis loop showing the plot of magnetic field (H) against magnetic

Table 1 Heat-treatment conditions and mechanical properties of samples used in the in-situ tensile tests

Sample ID	Water quenched / Water quenched and aged (K)	Vickers Hardness	UTS (MPa)
Sample–A	Water Quenched	297	995
Sample–B	675	322	1072
Sample–C	775	340	1118
Sample–D	875	271	953
Sample–E	950	253	933
Sample–F	975	273	882

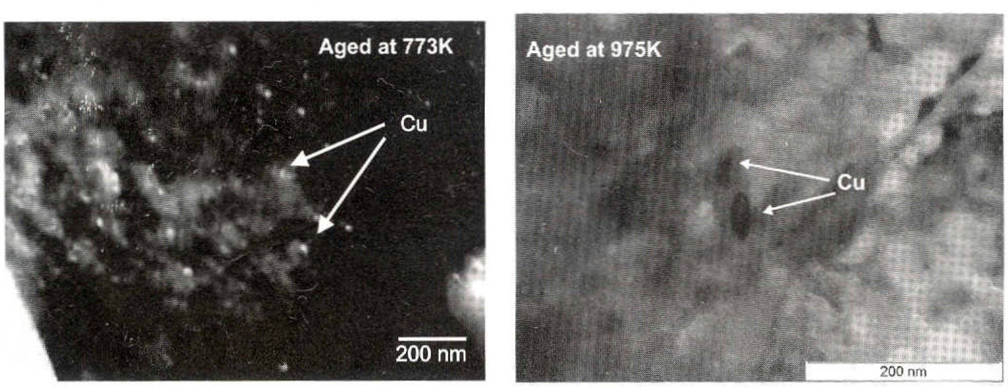
RESULTS AND DISCUSSION

The SEM and TEM microstructures of water quenched sample shown in Figure 2(a) and 2(b) respectively consisted of mainly lath martensite, acicular ferrite and bainite. The presence of small amount of retained austenite and $M_{23}C_6$ carbides, Nb(CN), TiN in the matrix was also observed. In sample # A which was austenised at 1183 K for one hour and water quenched, Cu present within the material was solutionised and α-iron was supersaturated with Cu. However, during subsequent heat-treatment Cu was precipitated due its low solubility (0.2%) in α-Iron. The precipitation of such Cu during ageing was observed by TEM study. Figure 3(a) showed the TEM micrograph of copper precipitation in the material aged at 773 K. It showed the clustering of very fine coherent precipitation of ε-Cu. The similar precipitates were observed in the materials aged up to 823 K whereby the size of these copper precipitates was less than 20 nm. At higher temperatures, these ε-Cu precipitates started coarsening in the 2nd stage of ageing, i.e beyond 823K and rod shape fcc Cu-precipitates were observed. The growth of rod like incoherent fcc copper precipitates from tiny spherical copper rich particles is shown in TEM image of Figure 3(b) where the material was aged at 973K. This microstructural development was attributed to the growth of coherent ε-Cu precipitates during over aging and subsequent loss of coherency.[3–5]



(a) (b)

Fig. 2 (a) SEM microstructure of water quenched (WQ) HSLA-100 steel and (b) TEM bright field (BF) image of the WQ HSLA-100 steel showing lath martensite, acicular ferrite.



(a) (b)

Fig. 3 (a) TEM micrograph of aged (773 K) specimen showing fine copper precipitates (b) Bright field TEM micrograph of aged (973 K) specimen showing rod shape incoherent copper precipitates

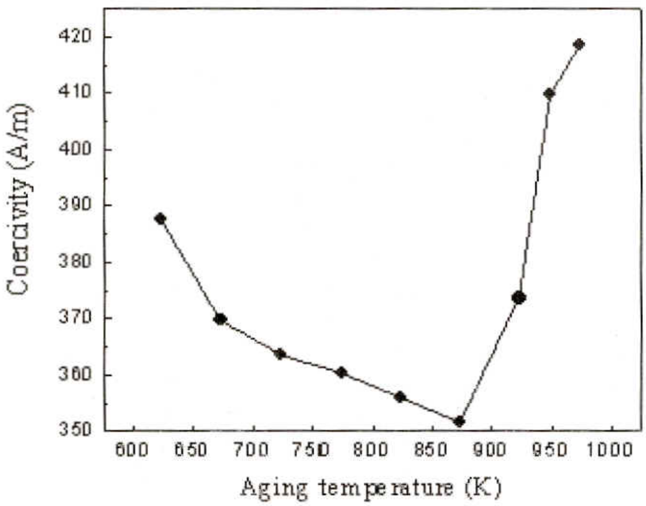


Fig. 4 Variations of magnetic coercivity with the aging temperature.

Figure 4 shows the ageing behaviour of the magnetic coercivity of the steel. With the increase of ageing temperature the coercivity decreased indicating magnetic hardness in spite of increase of mechanical strength. The microstructural study indicated that the nano-sized coherent Cu precipitation took place during initial stage of ageing which is the cause of increase in mechanical strength. However, such Cu precipitation does not affect the magnetic property as long as their size is less than the domain wall width. The magnetic softness at the initial stage of ageing was due to the grain growth and relaxation of quenched stresses. As soon as the precipitation size became more than the domain wall width, sharp deterioration in magnetic property was observed.

For the study of magnetic behaviour during tensile deformation, six HSLA-100 steel specimens bearing the same nominal composition were selected consisting of water quenched (sample #A) and aged from 675 K–975 K (sample # B to F). Figure 5 shows the variations of coercivity of the samples under tensile deformation together with the stress-strain curves. The coercivity values were normalised with respect to the value at zero strain. Initially, coercivity HC decreased rapidly with strain below the yield point for all samples. This decrease was mainly due to the positive magnetostriction of the Fe-based alloys that makes the process of magnetisation along the stress axis easier during the application of tensile stress. However, for the subsequent stages of deformation at higher strain levels, HC behaved differently depending on the initial heat-treatment conditions of the samples. In the case of water quenched sample #A, when strain was increased above the yield point (yield stress = 818 MPa), the rapid decrease in HC reduced with a tendency to maintain consistency till the strain level reached the ultimate tensile stress (UTS). This magnetic behaviour was more prominent in sample # B aged at 675 K whereby the coercivity slightly increased above yield point. When the strain was above the corresponding UTS value, the coercivity suddenly dropped after an initial increase and then decreased slowly with the tensile strain until the fracture took place.

In the case of sample # C aged at 775K, HC decreased slowly although the slope changed after reaching the yield point. For strain level higher than the corresponding UTS value, the HC of sample B again increased with strain. For sample # D where the Cu precipitates became incoherent, the variation of HC was different from other measured samples. In this case, HC decreased and leveled off near the UTS, above which it started decreasing again until failure. The elongation of this sample was the largest among the three measured samples.

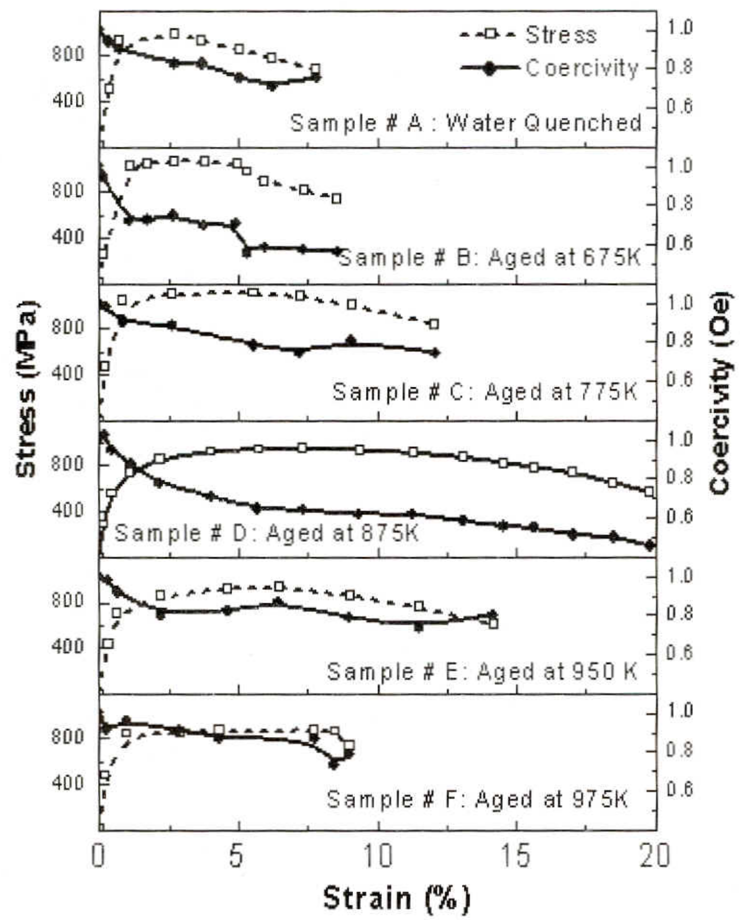


Fig. 5 Variations of coercivity and stress with strain for the six HSLA-100 samples A to F for water quenched and different ageing temperatures.

Microstructural investigation of the fracture surfaces using an SEM revealed different failure mechanisms of the samples. Figure 6 (a, b, c and d) shows the fractographs of the measured samples. Water quenched sample # A showed small equi-axed and shallow microvoids. In sample # B (675 K aged) where coherent nanosized Cu-precipitation was predominantly responsible for the increase in hardness, quasi-cleavage fracture surfaces were observed indicating that the materials became brittle. In this material, at the yield stress, the dislocation movement was hindered by the coherent precipitation of Cu. The coercivity at this point increased due to the interaction of domain walls with dislocations. As soon as the dislocations started moving, the domain walls became unpinned and abrupt decrease in the coercivity was observed. The formation of voids above the yield stress also played a role in the observed change of coercivity prior to failure. For sample # C which was aged at 775 K, there was co-existence of coherent and incoherent nanosized Cu precipitates which was reflected in the fractograph with a mixed type of fracture surfaces, quasi-cleavages (brittle fracture) and dimples (ductile fracture). The ductility of this sample also increased. Although the dislocation movement was restricted at the site of coherent precipitation which was responsible for brittle fracture, the dislocations could move easily at the site of incoherent Cu precipitates. This was also shown in the coercivity measurements. Distinctive changes in slope of coercivity with strain were observed above the yield stress. When the sample was aged at a higher temperature, for example at 875 K for sample # D, incoherent precipitation was dominant as was evident from the drastic fall in hardness (from 322 VHN for sample B to 271 VHN for sample D). The sample behaved more like a ductile material and the dimpled fracture surface [Fig. 6(c)] also confirmed the ductile nature of the sample. The coercivity decreased with strain and leveled off at a higher strain value. At a strain value corresponding to UTS, the decrease of HC might be due to the coalescence of voids that reduce the domain wall pinning density.

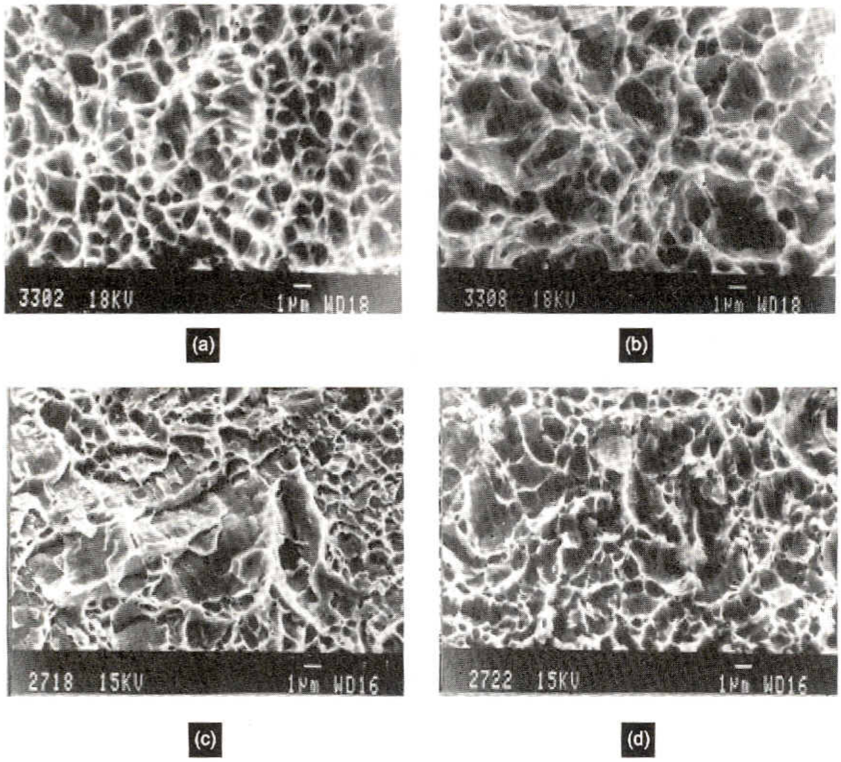


Fig. 6 SEM micrograph of the fractured surface (a) Water quenched (b) sample A aged at 675 K (c) sample B aged at 775 K and (d) sample C aged at 875 K.

In the case of sample aged at still higher temperature of 950 K and 975 K, the material showed more prominence in the increase of coercivity beyond yield strength and upto UTS. This was attributed to the impediment of the domain wall movement due to the large dislocation density owing to the regeneration of martensite from austenite. This behaviour was also observed from the increase in hardness from 253 to 273 when ageing temperature was increased from 950 K to 975 K also leading to brittle fracture.

CONCLUSION

Magnetic hysteresis properties evaluated for Cu-containing HSLA-100 steel indicated variations in coercivity during tensile deformation. The nano-sized Cu precipitates did not reveal any direct influence on the magnetic properties, the interaction of the dislocations with the coherent and incoherent Cu precipitates during plastic deformation affected the evolution of magnetic properties as plastic strain increased. The investigation indicated that magnetic measurement techniques can be used for studying the mechanism of fracture at a microscopic level.

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