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Mechanical properties of a cold-rolled annealed HSLA steel

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Hot rolled strips of an HSLA steel containing niobium and vanadium were cold rolled in the range 15 to 80% and annealed for 1 h at various temperatures from 400 to 700 °C. The response to the amount of deformation and annealing temperature were studied in terms of changes in its hardness, tensile strength and ductility. Hardness and strength were observed to increase while ductility decreased with the amount of deformation. Although annealing of the steel up to 500 °C did not show significant changes in its mechanical properties, a sharp decrease in hardness and strength and improvement in ductility were observed on annealing the steel at temperatures greater than or equal to 600 °C. Microstructural studies showed complete recrystallization in the samples subjected to 60% deformation followed by annealing at 600 °C.

1. Introduction

In the past two decades rapid developments have taken place in high strength steels used for transport vehicles with a view to reducing their overall dead weight [1]. This has become all the more important in view of the necessity to conserve energy and reduce consumption of fuel in automobiles [2]. Cold-rolled, annealed mild steel sheets have been used for many years to fabricate a variety of components needed by the automobile industry [3]. The main advantage of mild steel, and hence its widespread use as a structural material in the automobile industry, is its low cost and ease of fabrication [4]. Vastly improved techniques in steel making in recent years have, however, given rise to the production of high strength low alloy (HSLA) steels [5]. These steels not only possess a higher tensile strength but also have adequate notch toughness and weldability. All these desirable properties are obtained by a judicious adjustment of its chemical composition and the implementation of a controlled rolling schedule. Although a large number of investigations have been carried out in order to understand the microstructural development during controlled rolling of HSLA steels [6], surprisingly only limited investigations have been done on cold rolling and annealing of HSLA steels. The present work constitutes an attempt in this direction.

2. Experimental procedure

The chemical composition and mechanical properties of hot-rolled HSLA steel used in the present investigation are shown in Table I. Hot bands of HSLA steel, supplied as sheets of approximately 5.5 mm thickness, were subjected to various cold reductions in a two-high rolling mill.

These sheets were rolled at room temperature from 15% to 80% reduction in thickness. Samples for metallography and mechanical testing were fabricated from each of these cold-rolled sheets. The gauge length of the tensile sample was kept parallel to the rolling direction and subjected to annealing at four different temperatures, i.e. 400, 500, 600 and 700 °C. The annealing time at each of these temperatures was maintained for precisely 1 h. Specimens for microstructural examination were prepared using standard metallographic techniques and observed in a Leitz Panphot optical metallograph. The hardness of the samples was measured using a Vickers hardness testing machine using a load of 20 kg. The tensile tests were performed on a 10 T Instron machine.

3. Results

3.1. Mechanical properties

The hardness, yield and tensile strength of the steel continuously increased with the amount of deformation whereas the fracture strain, which is a measure of the ductility of the material, and the area under the stress–strain curve, which represents its toughness, decreased.

Annealing up to 500 °C of the steel samples, given less than 45% deformation, did not show any appreciable drop in hardness and strength. Samples deformed above 45%, i.e. 60% and 80%, showed a drastic drop in hardness on annealing at 500 °C (Fig. 1). Similar changes were observed in yield and tensile strengths of the steel. It can be seen that hardness is a strong function of cold work even up to 500 °C. Further increase in annealing temperature, resulted, however, in a close match of hardness values, pertaining to different amounts of prior cold work. Plot of yield and ultimate tensile strengths as functions of annealing temperature are shown in Fig. 2. Once again a similar

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TABLE I Composition and mechanical properties of hot-rolled HSLA steel

Composition (wt %)					Mechanical properties		
C	Mn	Si	Nb	V	Yield strength (kg mm^{-2})	Ultimate tensile strength (kg mm^{-2})	Elongation (%)
0.12	1.01	0.07	0.04	0.04	40	54	20

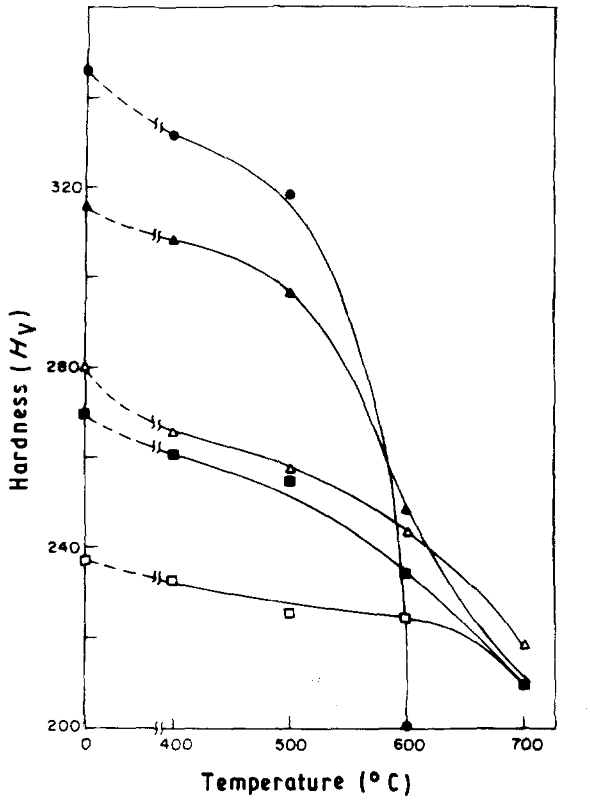


Figure 1 Effect of annealing temperature on hardness of cold-rolled HSLA steel. (Deformations: □ 15%, ■ 30%, △ 45%, ▲ 60%, ● 80%).

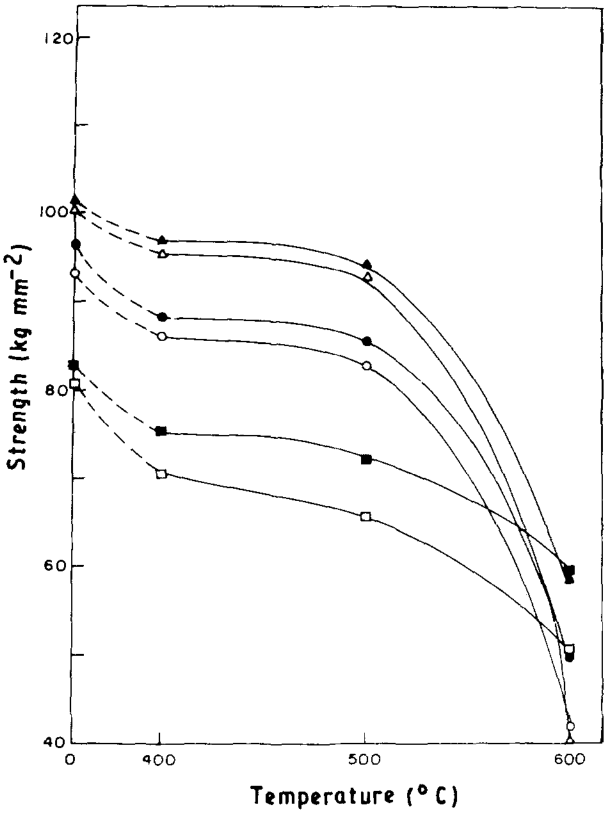


Figure 2 Variation in yield and ultimate tensile strength as a result of deformation and annealing. (Deformations: ▲ UTS 60%, △ YS 60%, ● UTS 45%, YS ○ 45%, ■ UTS 30%, □ YS 30%).

dependence of the strength on annealing temperature for all the samples given different cold work can be noticed.

An attempt to correlate the hardness values with the yield and tensile strengths of the samples studied in the present investigation is shown in Fig. 3. The following empirical relationships were observed:

$$\sigma_T = 0.588\,H_V - 79.81 \qquad (1)$$

$$\sigma_y = 0.688\,H_V - 111.08 \qquad (2)$$

where σ_y and σ_T are the yield and tensile strength, respectively, measured in kg mm^{-2} and H_V is the Vickers hardness number. Both yield strength as well as tensile strength are observed to vary linearly as functions of hardness. It is, however, interesting to note that the yield strength equals the tensile strength at a hardness of around 330 H_V which apparently could be obtained in a sample given 80% cold deformation (Fig. 1).

The effect of annealing temperature on the ductility and toughness of the steel is shown in Figs 4 and 5. The cold-deformed samples exhibit the lowest ductility and toughness values. Ductility and toughness continue to be low, even on annealing at 500 °C. A marked rise in these properties is, however, noticed on annealing the cold-rolled steel at 600 °C. The above observations indicate that the steel samples subjected to different amounts of deformation might result in complete recrystallization when annealed at 600 °C. The degree of cold deformation prior to annealing also has a strong influence on ductility and toughness of the steel. 45% prior cold work and a subsequent anneal at 600 °C appears to give the best toughness and ductility values to the steel (Figs 4 and 5).

3.2. Microstructural features

Optical metallography of the samples annealed at 400 °C did not reveal any observable change in the microstructure in comparison to the respective cold-rolled structures. Annealing above 500 °C, however, exhibited a marked change in the microstructure of highly deformed specimens. Fig. 6a to c shows the microstructures of the steel subjected to three different

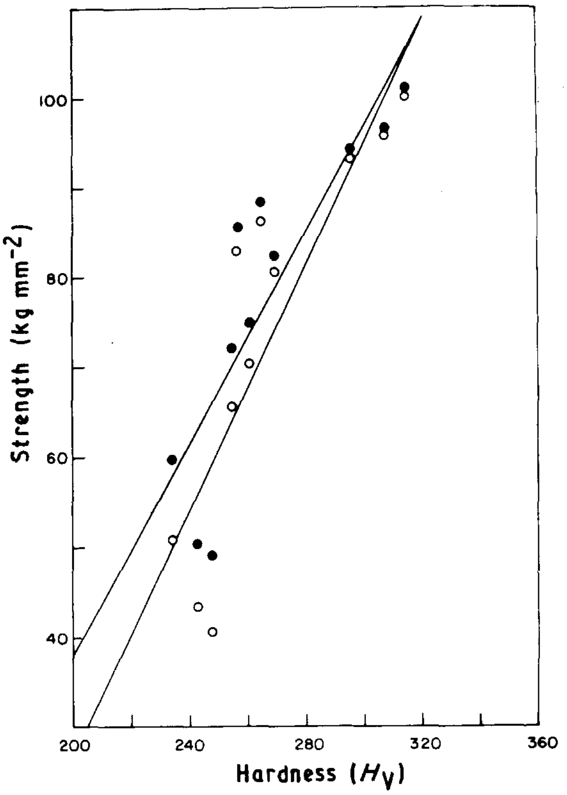


Figure 3 Correlation between strength and hardness of cold-rolled, annealed HSLA steel. (● UTS, ○ YS).

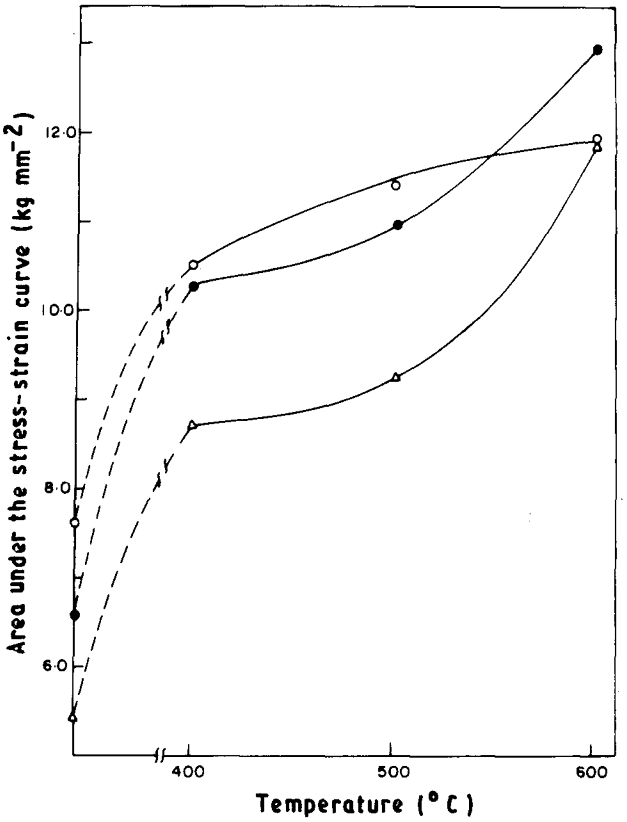


Figure 5 Variation in toughness of cold-rolled, annealed HSLA steel. (Deformations: ○ 30%, ● 45%, △ 60%).

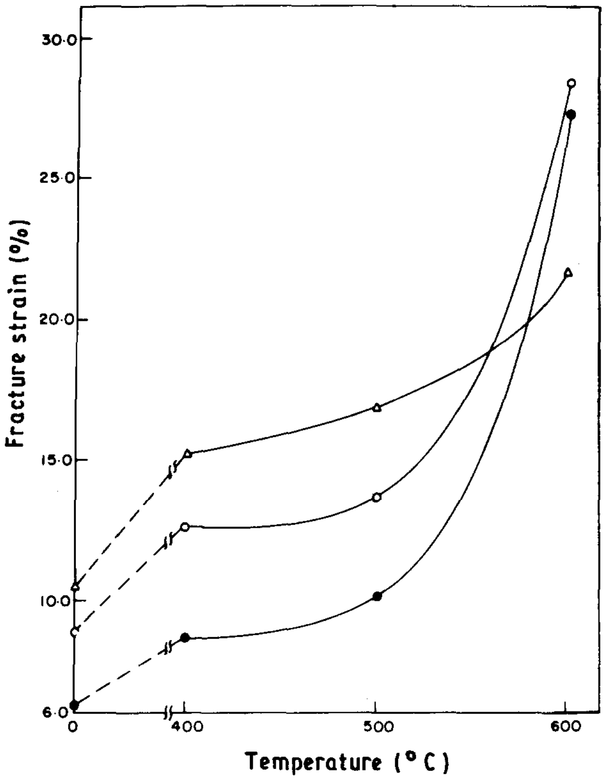


Figure 4 Effect of annealing temperature on fracture strain of cold-rolled samples. (Deformations: △ 30%, ○ 45%, ● 60%).

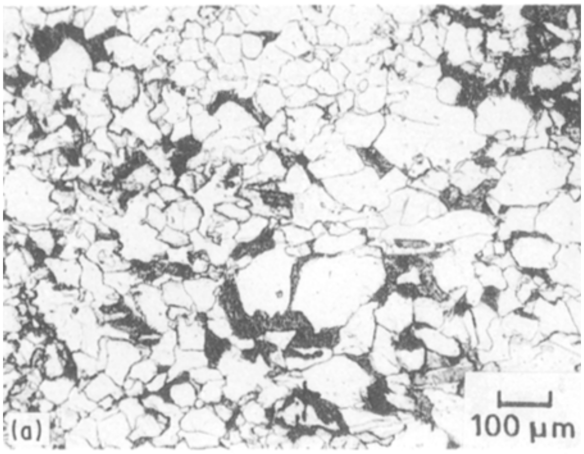
deformations (i.e. 30, 45, and 60%) and their subsequent annealing at 500 °C. Mixed grain structure, a characteristic feature of partially recrystallized materials, can be distinctly observed in the micrographs of samples given 30 and 45% deformation. On the other hand, fine equiaxed ferrite grains are noticed in the microstructure of the sample given 60% deformation. Further, the volume fraction of the recrystallized grains is significantly larger in samples subjected to 60% deformation (Fig. 6c) as compared to those given lesser deformation (Fig. 6a and b).

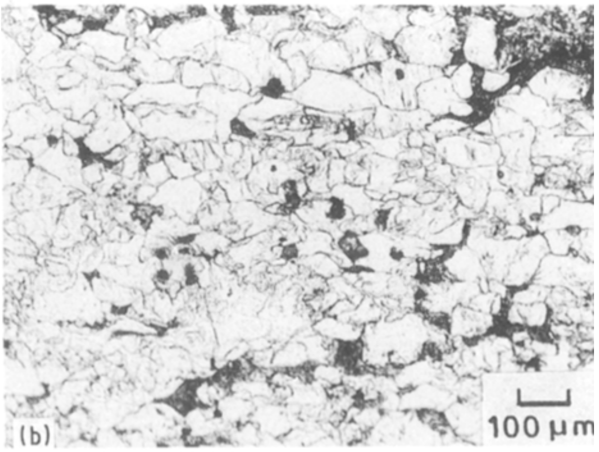
The typical microstructures of the samples annealed at 600 °C are presented in Fig. 7a to c. These micrographs clearly reveal the presence of uniform equiaxed grains. Nevertheless, the recrystallized grain size of the specimens for a specific annealing temperature continuously decreases with increase in the degree of deformation. Examination of the samples annealed at 700 °C shows complete spherodization of the cementite as shown in Fig. 8a and b. Further, at this annealing temperature, ferrite grains of heavily deformed samples are observed to coarsen.

4. Discussion

In assessing the results of the present investigation it is particularly important to compare the mechanical properties of the steels with their microstructural features. All the samples annealed at 600 °C have shown fairly close hardness values (Fig. 1). The microstructural studies of these samples showed uniform, equiaxed grain characteristics of a recrystallized steel (Fig. 7). The steel deformed by 80%, however, showed a sharp decrease in the hardness value upon annealing at 600 °C. The variation in the yield and tensile strength also reflected a similar trend with the temperature of annealing.

The above results indicate that the recrystallization temperature of the severely deformed samples is relatively low. The difference in hardness values of the





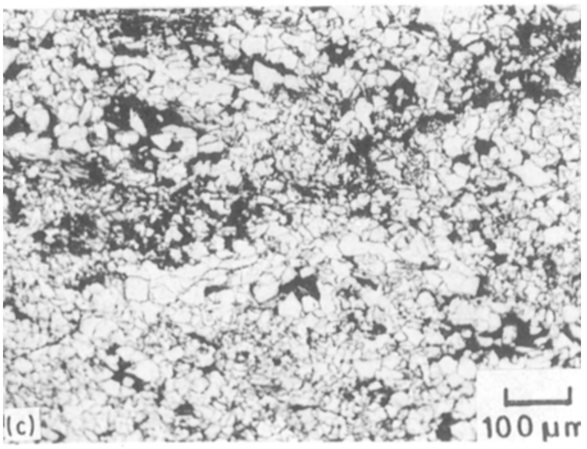
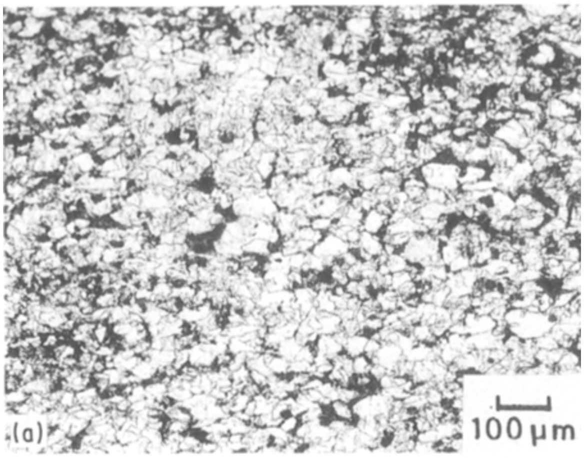
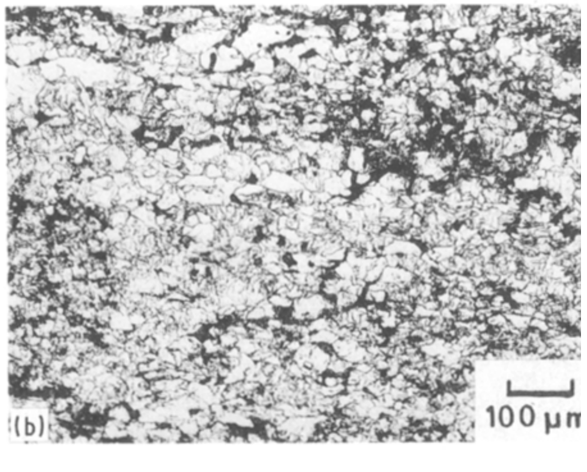


Figure 6 Photomicrographs of steels deformed at (a) 30%, (b) 45% and (c) 60% and subsequently annealed at 500 °C.

samples annealed at 600 °C further confirm this view. The present work thus shows that steels given heavy cold reduction begin to recrystallize at a lower temperature and is completed more quickly. Such samples show distinctly fine grain size compared to those given a light cold reduction. These effects of a severely deformed sample can be considered to be due to greater number of sites for recrystallization to initiate. It has been reported [7] that, as the cold work increases, the stored energy – a measure of the driving force for crystallization – increases. The rate of change of hardness values of the steels annealed at different temperatures, as shown in Fig. 1, further supports this conclusion.

The effect of prior annealing treatment on recrystallization behaviour of a plain carbon and HSLA steel has been reported [8]. By hardness measurements it was shown that the samples, annealed at intermediate temperatures, had a longer incubation period for recrystallization. The incubation period decreased with increase in the annealing temperatures from 600 to 650 °C. It was explained by these investigators that subcritical annealing led to recovery of the defect structure and thereby the total stored energy required





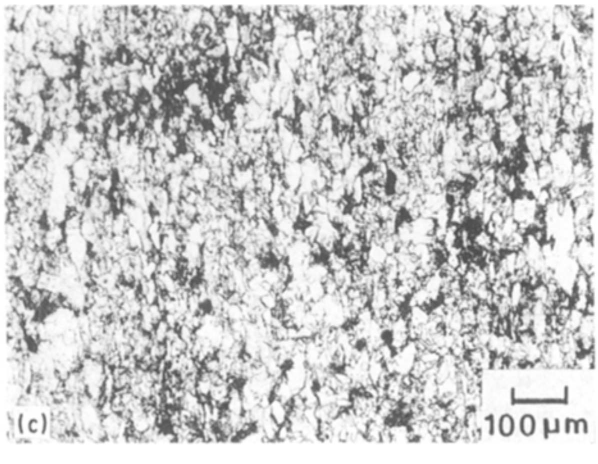


Figure 7 Photomicrographs showing recrystallized ferrite grains in specimens which have been pre-deformed to (a) 30% (b) 45% and (c) 60% and annealed at 600 °C.

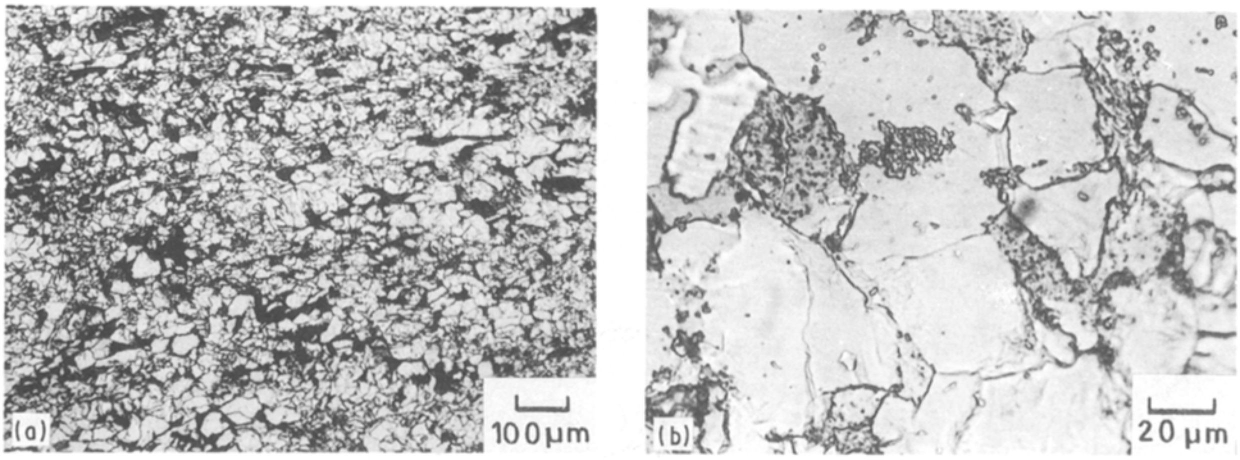


Figure 8 Micrographs of the samples annealed at 700 °C after 60% deformation showing spherodized cementite particles.

for recrystallization decreased. This effect was attributed to lower nucleation rates of the recrystallized grains in the pre-treated samples resulting in difference in grain size. Since, in the present work all the deformed samples were directly annealed at different temperatures, the difference in their recrystallization temperatures and grain sizes can be considered to be only a function of the amount of stored energy in the material.

The composition and precipitate size are also known to influence the recrystallization temperature of the steel. In another investigation [9] it was shown that niobium and manganese significantly raise the recrystallization temperature. A 60 °C rise in the recrystallization temperature was observed by these workers when the manganese content in steel increased from 0.39% to 1.25%. Similarly an increase in niobium from 0.045% to 0.09% raised the recrystallization temperature by 39 °C. It was also influenced by the precipitate size present in the steel prior to cold rolling. Fine precipitates significantly raised the recrystallization temperature.

The hot bands of HSLA steel used in the present investigation has niobium carbide and carbonitride precipitates of 0.1 to 0.5 µm. These fine precipitates coupled with presence of niobium and vanadium in solid solution with ferrite are expected to raise the recrystallization temperature of the present steel compared to those of plain carbon steel. Only the samples subjected to at least 60% deformation and annealed at 600 °C have thus shown complete recrystallization as is observed in the hardness variation and microstructural studies. A sharp decrease in the hardness of the sample, annealed at 700 °C, can be attributed to spherodization of cementite (Fig. 8). The results of the present investigation thus indicate that by proper design of cold deformation and annealing cycle of an HSLA steel a range of strength and toughness properties can be achieved. The present investigation suggests an optimum combination of 45% prior cold work and a subsequent anneal at 600 °C as seen in Figs 4 and 5.

5. Conclusions

Wide ranges of strength and toughness of a Nb–V containing HSLA steel are obtained by cold deformation and annealing treatment. The rate of change in hardness and strength depends upon the amount of deformation and annealing temperatures. Steels severely deformed above 60% show full recrystallization by annealing at 600 °C. This is reflected by a sharp decrease in its hardness and strength and increased ductility and toughness. By optimum control of cold deformation and annealing cycle steels having tensile strength from 60 to 80 kg mm^{-2} with a ductility of 30 to 22% can be achieved. 45% prior cold work and a subsequent anneal at 600 °C is found to impart the maximum toughness and ductility to the HSLA steel in the present investigation.

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References

1. S. ASAKURA, K. KOSHINO and N. IWASAKI, *Trans. Iron Steel Inst. Jpn* **21** (1981) 767.
2. F. L. GREEN, "Microalloying 75" (Union Carbide Corporation, New York, 1977) p. 634.
3. R. D. BUTLER and J. F. WALLACE, "Recent Developments in Annealing" (Special Report 79) (The Iron and Steel Institute, London, 1979) p. 131.
4. K. YOSHIDA, *Trans. Iron and Steel Inst. Jpn* **21** (1981) 761.
5. B. K. PANIGRAHI, S. MISHRA and S. SEN, *Trans. Ind. Inst. Metals*, **39** (1986) 241.
6. T. TANAKA, *Int. Met. Rev.* **4** (1981) 185.
7. P. COTTERILL and P. M. MOULD, "Recrystallisation and Grain Growth in Metals" (Surrey University Press, London, 1976).
8. J. CEARCIA-VARGAS, D. A. HARDWICK and W. M. WILLIAMS, *Can. Met. Quart.* **19** (1981) 333.
9. I. GUPTA and I. F. HUGHES, "Microalloying 75" (Union Carbide Corporation, New York, 1977) p. 303.

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