The strengthening factors of thermo-mechanically treated high carbon steels

In recent years considerable research effort has been devoted to increasing the strength as well as the toughness of certain carbon and low-alloy steels by thermomechanical treatment (TMT). Grange [1] has described how the principles of fibre composite strengthening can be applied to a limited extent in steels which have a pearlite structure by developing *in situ*, a reinforcing, oriented, strong, fibrous constituent. In the case of oriented coarse pearlite in eutectoid carbon steel, strengthening is produced by rolling, followed by a rapid reheating to a temperature slightly above A_1. The treated material was found to have not only a higher strength, but also a higher ductility than the corresponding randomly oriented pearlite in a typical eutectoid pearlite structure. Materials treated as above can usually be included in low temperature thermomechanical treatments [2] (LTMT). Dislocation density is always increased and some dislocation cells may be formed in metals after plastic deformation. Redistribution of dislocations takes place during thermal treatment, and leads to the formation of small new subgrains after an LTMT process. Apart from composite strengthening, the existence of subgrains should also play an important role on the tensile properties of the treated steel. As far as we are aware, none of the previous works has made an intensive study on the improvements of tensile properties in terms of both subgrains and composite strengthening.

In the present study, common high carbon steels having eigher a coarse lamellar pearlite or spheroidal structure were treated using the LTMT process. Both kinds of sample treated showed good improvements in tensile properties which were attributed to both composite and subgrain strengthening.

Commercial common high carbon steel having a chemical composition (as shown in Table I) close to eutectoid carbon steel, was chosen for this experiment.

In order to facilitate comparison, samples with approximately the same grain size were prepared before the LTMT process. These are (1) lamellar coarse pearlite having a random orientation (L), and (2) spheroidal pearlite (S). Both kinds of sample were cold-rolled to a 75% reduction in area and then heated in a lead bath for 12 sec at 760° C, followed by air cooling. Sample 1 was called LRQ, and sample 2 SRQ, after the LTMT process had been carried out. Certain preferentially oriented carbides were found in all samples of LRQ, and grains were also elongated in the rolling direction.

TABLE 1 Chemical composition of the steel (wt %)

C	Cr	Cu	Mo	Ni	P	S	Si
0.92	0.17	0.122	0.013	0.047	0.02	0.018	0.35

TABLE II Effect of the LTMT process for lamellae pearlite and spheroidal pearlite on tensile properties

Sample	Yield strength ($kg\,mm^{-2}$)	Ultimate tensile strength ($kg\,mm^{-2}$)	Elongation (%)
L	38.2	76.4	7.8
S	40.5	70.6	23
$LRQ_{\parallel}$	64.5	82.9	13.5
$LRQ_{\perp}$	67.4	90.2	6.8
SRQ	60.7	72.5	12

TABLE III Percentage increase in tensile properties after LTMT

Sample	Yield strength (%)	Ultimate tensile strength (%)	Elongation (%)
$L \rightarrow LRQ_{\parallel}$	+ 69.5	+ 8.6	+ 73
$L \rightarrow LRQ_{\perp}$	+ 77	+ 18.1	− 12.8
$S \rightarrow SRQ$	+ 50	+ 3.6	− 48

The tensile properties of all samples were studied using an Instron tensile machine Model 1115. Metallographic studies were carried out using both optical microscopy and scanning electron microscopy. The internal microstructures of all samples were observed by transmission electron microscopy using the thin foil technique.

Tables II and III compare the tensile properties of samples having the coarse lamellar pearlite (L and LRQ) and the spheroidal pearlite (S and SRQ) before and after the LTMT process.

$LRQ_{\parallel}$ ($LRQ_{\perp}$) indicates LRQ samples tensile tested with the tension parallel (perpendicular) to the rolling direction. Strength, especially the yield strength, as well as ductility (on the basis of elongation) are substantially higher for oriented

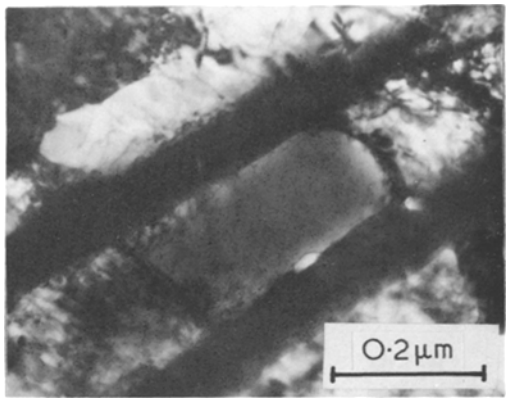

Figure 1 TEM micrograph of coarse lamellar pearlite rolled to a 75% reduction in area.

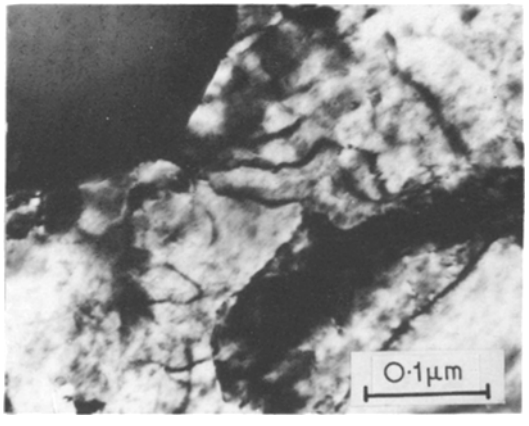

Figure 2 TEM micrograph of spheroidal pearlite rolled to a 75% reduction in area.

lamellar pearlite ($LRQ_{\parallel}$) than for randomly oriented lamellar pearlite (L). Grange [1] suggested that improvements in both strength and elongation were due to the effect of composite strengthening. However, from Tables II and III, it can be seen that although the elongation is reduced, the strength (including yield strength and ultimate tensile strength) of oriented lamellar pearlite ($LRQ_{\perp}$) tested with the tension perpendicular to the rolling direction is even higher than that of oriented lamellae pearlite ($LRQ_{\parallel}$) tested with the tension parallel to the rolling direction. In addition, a large increase in yield strength was observed for the spheroidal pearlite (SRQ), in which the phenomenon of oriented carbides can be virtually neglected. Thus, evidently it is

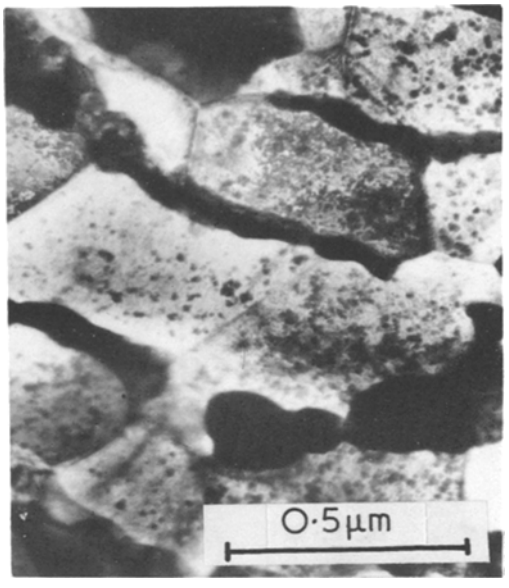

Figure 3 TEM micrograph of coarse lamellar pearlite after the LTMT process.

inappropriate to attribute the increase in strength to the composite strengthening mechanism alone.

One of the most important changes occurring with deformation in metals is the increase in dislocation density and the formation of dislocation cells according to the level of plastic deformation. It is also well understood that the internal microstructure does not always recover to the original condition under certain annealing processes after plastic deformation [2–4]. Subgrains are always fromed after an LTMT process.

It is well established that in relatively pure metals which have undergone static or dynamic recovery, the strength is highly influenced by the size and character of the subgrains [2, 4, 5]. In addition, if subgrains are formed in the matrix of a two-phase material, subgrain strengthening should be also an important factor in affecting the strength of the material.

Internal microstructures were observed by TEM using the thin foil technique during every critical step of the LTMT process. A highly tangled dislocation density and some dislocation cells as shown in Figs. 1 and 2 were produced by rolling samples L and S to a 65% reduction in area. Fig. 3 represents the microstructure in the sample with the coarse lamellar pearlite structure, after the

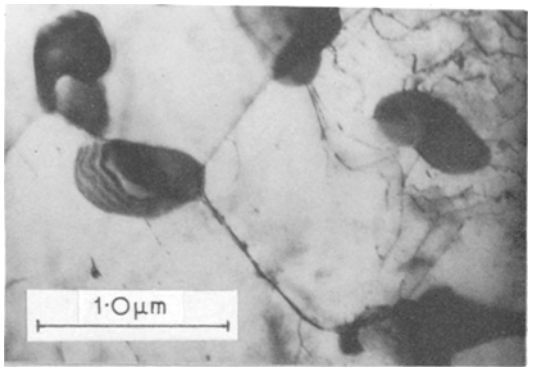

Figure 4 TEM micrograph of a sample of coarse lamellar pearlite after the LTMT process and a heating time of 90 sec. Some carbide precipitates can be clearly seen.

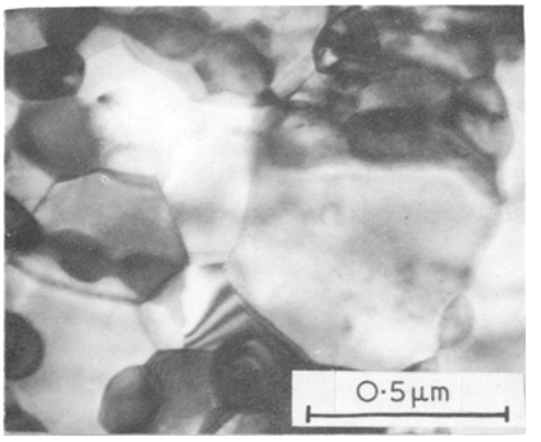

Figure 5 TEM micrograph of a sample of spheroidal pearlite after the LTMT process.

whole LTMT process. Subgrains with sharp boundaries are formed in the samples, varying in size from 0.5 to 2 μm. It can be seen from Fig. 3 that lamellar cementites serve as part of the subgrain boundaries and the subgrains are always located between the carbides. Some small particles of precipitated carbides plus some dislocation pile-ups are also seen in the same figure. The particles of carbide precipitate are more abundant if the heating time is increased. This phenomenon is shown in Fig. 4 for an LRQ sample which was subjected to a longer heating time (90 sec). Fig. 5 shows the microstructure in the spheroidal pearlite sample after the LTMT process, where the subgrain size is almost the same as in the LRQ samples.

Much work [6–8] on the dependence of strength on subgrain and cell sizes has been carried out. However, few works report the subgrain strengthening in a two-phase material [3]. The quantitative analysis of subgrain strengthening for a two-phase material is complicated because the orientation, size or shape of the second phase will also be changed if one tries to change the size of the subgrain. In our case for example, the subgrain size can be increased either by lengthening the heating time or by changing the reduction ratio of plastic deformation. However, by doing so either the precipitated particles of carbide will be increased (as shown in Fig. 4), or the amount of preferential orientation of lamellar carbide will be changed. We have shown here qualitatively the experimental evidence of subgrain strengthening for high carbon steel after the LTMT

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