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Effect of Degree of Deformation on the Mechanical Properties of High Temperature Thermomechanically Treated Steel

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Abstract: The development of high strength materials, coupled with good formability, has always been the aim of material scientists. The effect of degree of deformation on the mechanical properties of high temperature themomechanically treated steel (HTMT) has been investigated in this study. It has shown that an increase in percent deformation results in improvement in mechanical properties. In order to have maximum strengthening, heavy deformation and low finishing temperature should be chosen.

Key words: Formability, deformation, strengthening, HTMT

INTRODUCTION

Thermomechanical treatment involves the deformation of austenite at a temperature above the recrystallisation temperature. The austenite formed is quenched immediately after mechanical working to avoid development of recrystallisation process. The strengthening achieved arises from austenite grain size refinement, but optimum properties are often obtained if austenite is prevented from recrystallisation (Hurley *et al*., 2000; Askeland, 1994; Kamma, 1990).The application of low stress and strain rates, presents rapid recovery rate and the materials do not dynamically recrystallise.Thus, a dislocation density and configuration sufficient to nucleate and drive the recrystallisation process is not developed in them. The degree of deformation in HTMT must not be excessively high; otherwise recrystallisation might reduce the strengthening effect (Novikov, 1978).

The grain size dependence of flow stress in metals is evident from the well known Hall-Petch relationship (Prasad, 1975). In fact, nowadays it has become fashionable to influence and control the mechanical properties of materials by systematic control of the grain structure and grain size (Hurley and Hodgson, 2001; Embury, 1975; Dahl and Rees, 1974). Thus, the ever growing interest of physical and mechanical metallurgists in grain-size controlling research efforts is understandable. The conventional method of grain refinement and improvement of mechanical properties is through the application of alloying elements. A rather unorthodox, but technologically viable method is the so-called thermo mechanical process employing heat treatment and mechanical deformation in a repetitive cycle-a familiar procedure in conventional rolling operations. In terms of economy, effectiveness and procedural reproducibility, the thermo mechanical treatment appears to be the best method of grain size control (Kamma, 1990; Bolton, 1988).

This study therefore seeks to investigate and establish the combined effect of HTMT and degree of deformation in order to achieve optimum results.

MATERIALS AND METHODS

The sample was a low carbon steel obtained from Universal Steel Ikeja Lagos Nigeria with following composition (wt%) C-0.368, Si-0.226, S-0.033, P-0.039%, Mn-0.688, Ni-0.177, Cr-0.119, Mo-0.021, V-0.002, Cu-0.227%, W-0.003%, As-0.014%, Sn-0.003%, Fe-98.055%. The samples were in 16 mm, 12 mm and 10 mm diameter. The sizes were obtained by repetitive (cyclical) process of rolling and recrystallisation (HTMT) carried out a number of times resulting in varying degree of deformation. At the end of the HTMT, the samples were examined for microstructure. Tensile (strength), impact and hardness samples were prepared from different sizes.

The study was carried out in February, 2000 in the Materials Laboratories of the Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure, Nigeria; Obafemi Awolowo University, Ile-Ife, Nigeria and in the Department of Mechanical Engineering, Federal Polytechnic Ado-Ekiti, Nigeria.

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Calculation of the degree of deformation of the samples: Initial dimension of the billet = 100×10×10 cm
Initial cross sectional area of the billet = 10×10 = 100 cm^2 = 10000 mm^2

- For 10 mm diameter sample, cross sectional area = πr^2 = $3.142\times5^2 = 78.55$ mm^2

$$\% \text{ reduction in area} = \frac{10000\text{-}78.55\times100\%}{10000}$$

$$\therefore \% \text{ deformation} = 99.22\ \%$$

- For 12 mm diameter sample, cross sectional area = πr^2 = $3.142\times6^2 = 113.11$ mm^2

$$\% \text{ reduction in area} = \frac{10000\text{-}113.11\times100\%}{10000}$$

- For 16 mm diameter sample, cross sectional area = πr^2 = $3.142\times8^2 = 201\ .09$ mm^2

$$\% \text{ reduction in area} = \frac{10000\text{-}201.09\times100\%}{10000}$$

$$\% \text{ deformation} = 98.87\%$$

CALCULATION OF THE AVERAGE GRAIN SIZE OF DEFORMED SAMPLE

The determination of the average grain size (D) according to Kamma (1990) was by the well known 'intercept method', based on calculations of the average cross-sectional area (Fk) of a circle(diameter, dmm) drawn on a micrograph of known magnification (V), whereby

$$F_k = \pi\ d^2\ /4\ (mm^2) \qquad (1)$$

Average cross sectional area of grain (Fm)

$$\% \text{ reduction in area} = \frac{Fk\times10^6\ (\mu m)^2}{(0.67n + z)V_2} \qquad (2)$$

$$D = \sqrt{Fm} \qquad (\mu m) \qquad (3)$$

Where :
z = number of grain lying completely within the circle.
n = number of grains intercepted by the circle
0.67 = Oertel factors

RESULTS AND DISCUSSION

The result of the mechanical tests carried out is presented in Table 1. The corresponding stress-strain curves are shown in Fig. (1-3) for the 10 mm diameter, 12 mm diameter and 16 mm diameter samples respectively.

The micrographs (Fig. 5-8) show the dark patches as the pearlite phase and the white patches as the ferrite phase (proeutectoid) because the carbon content of the alloyed steel falls within the hypo eutectoid range (Lakhtin, 1990).

From Table 1, it can be seen that the 10 mm diameter sample has the highest ultimate tensile strength (UTS),

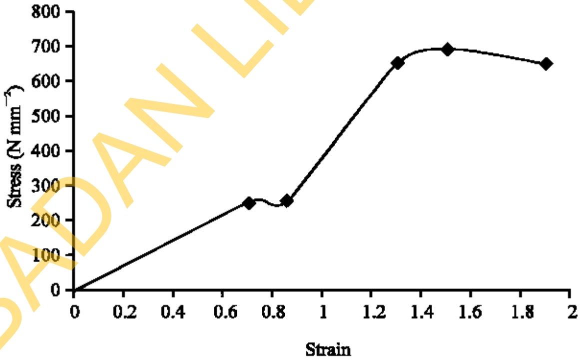

Fig. 1: Stress-strain curve for HTMT 99.2% deformation

Table 1:
A Tensile test
(i) 10 mm diameter as-rolled samples

Sample	Tensile load (N)	Elong-ation (%)	Reduction in area (%)	Fracture strength ($N\ mm^{-2}$)	UTS ($N\ mm^{-2}$)	Yield strength ($N\ /mm^{-2}$)	Cross-sectional area(mm^{-2})
1	13000	1.75	51.00	663.27	685.37	288.11	19.60
2	13035	1.81	51.70	665.05	686.41	240.49	19.60
3	13095	1.90	50.92	668.78	688.78	255.10	19.60
4	13250	1.72	52.00	694.56	694.56	286.70	19.60
(ii)	12 mm diameter as-rolled samples						
1	7200	4.80	56.38	367.35	377.55	239.80	19.60
2	7215	5.20	56.40	368.11	380.00	242.38	19.60
3	7156	4.50	56.45	365.10	374.47	237.26	19.60
4	7230	4.03	56.98	360.00	378.18	236.16	19.60
(iii)	16 mm diameter as-rolled samples						
1	4000	7.60	61.01	204.08	223.24	140.40	19.60
2	4100	7.75	61.25	209.18	219.58	145.48	19.60
3	4349	7.90	61.30	221.89	223.00	148.00	19.60
4	4300	8.00	61.48	219.39	221.94	147.00	19.60

(B) Hardness

Sample	10 mm diam	12 mm diam	16 mm diam
1	47.15	40.50	37.50
2	47.50	41.00	37.20
3	48.00	41.00	37.60
4	47.65	41.50	37.50

(C) Impact

Sample	10 mm diam	12 mm diam	16 mm diam
1	48.12	45.00	41.35
2	48.50	45.89	42.15
3	47.98	46.10	41.00
4	48.00	45.30	41.10

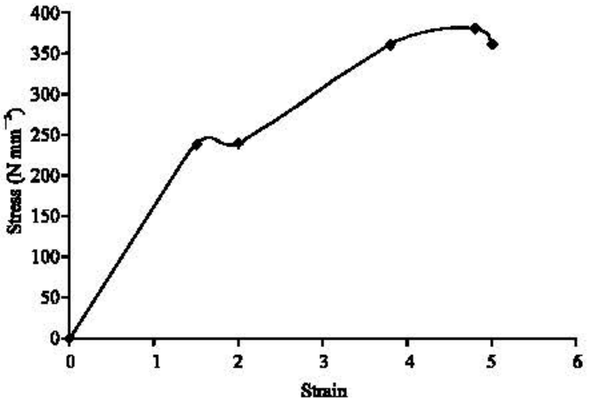

Fig. 2: Stress-strain curve for HTMT 98.78% deformation

Fig. 3: Stress-strain curve for HTMT 97.99% deformation

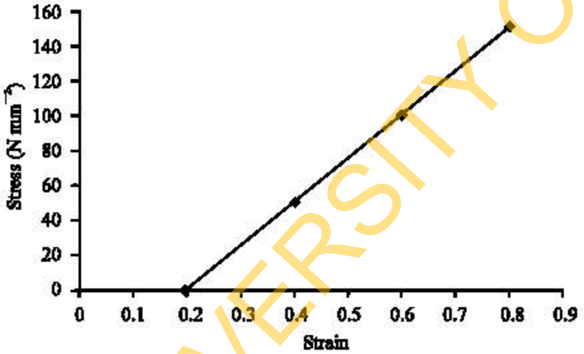

Fig. 4: Stress-strain curve for as-cast sample

followed by 12 mm diameter and 16 mm diameter respectively. The grain size decreases as the degree of deformation increases during the high temperature thermo mechanical treatment (Bolton, 1988). Thus, the 10 mm diameter sample, with the finest grains, explains strengthening by ferrite grain refinement. This is confirmed by the Hall-Petch equation:

$$\sigma_y = \sigma_i + k_y d^{-1/2}$$

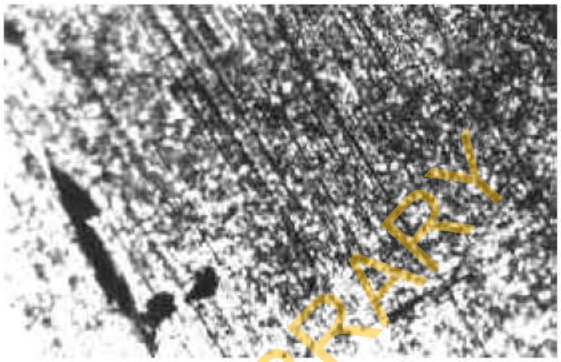

Fig. 5: 10 mm diameter as-rolled (HTMT) sample showing pearlite (dark patches) and ferrite (white patches) Magnification×100 Etchant -Nital

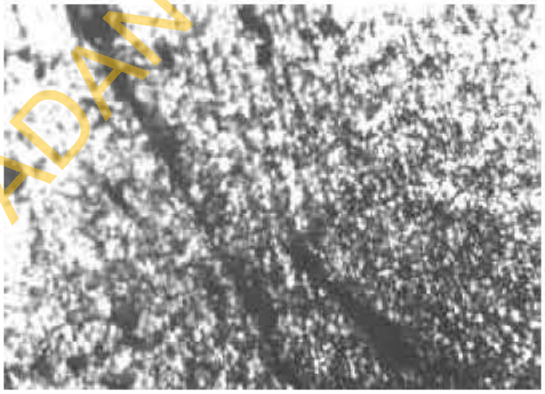

Fig. 6: 12 mm diameter as-rolled (HTMT) sample showing pearlite (dark patches) and ferrite (white patches) Magnification×100 Etchant -Nital

Fig. 7: 16 mm diameter as-rolled (HTMT) sample showing pearlite (dark patches) and ferrite (white patches). Magnification×100 Etchant -Nital

Where σ_y = yield strength, σ_i = friction stress, k_y = a constant, d = ferrite grain size.

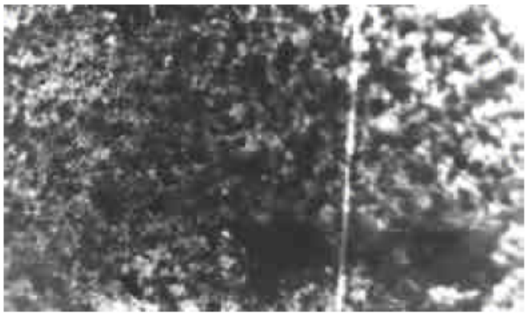

Fig. 8: As-cast sample showing pearlite (dark patches) and ferrite (white patches) Magnification×100, Etchant -Nital

It shows that the strength increases as the grain size decreases (Llewellyn, 1992). Microstructurally, Fig. 5, shows the best dispersed structure and the least presence of inclusions, blowholes and internal coring which contributes to the highest strength value. The dispersion fineness and uniformity trend in the micrographs are in the order of Fig. 5 >Fig. 6 >Fig. 7 >Fig. 8.

In terms of ductility, Table 1 columns for percent elongation and percent reduction in area show that the 16 mm diameter sample is the most ductile. Its relatively coarse grain (Fig. 7) enhanced ductility because more slippage can take place during plastic deformation before fracture (Lakhtin, 1990). Also, as the degree of deformation increases, the more difficult deformation or slippage becomes. Hence, the fewer the grain boundaries present, the better the ductility (Bolton, 1988).

In terms of hardness, Table 1 shows that the 10 mm diameter sample is the hardest. The high temperature thermo mechanical treatment confirms that as the degree of deformation increases, the strength and hardness increase concurrently (Bolton, 1988). From Fig. 5, the 10 mm diameter sample has the finest grains (many grain boundaries), poor ductility, giving rise to more resistance to deformation due to the repeated strain hardening during the working (HTMT). In the other plates, namely Fig. 6 and 7, respectively there is relative increase in grain size in that order over that in Fig. 8 where there is no thermomechanical working. As such the grain size in Fig. 4 remains the same.

The toughness property is highly sensitive to change in grain size. Therefore, the smaller the grains, the tougher the sample becomes (Novikov, 1978). Hence, from Table 1, the 10 mm diameter sample is the toughest. The Petch equation linking toughness to grain size is given by:

$$\beta T = \ln \beta - \ln C - \ln d^{-1/2}$$

where β and C are constants
T = impact energy (toughness)
d = ferrite grain size

CONCLUSIONS

This study has now established the fact that the coarser the grains, the better the ductility because more extensive slippage can take place during plastic deformation before fracture (Lakhtin, 1990). As the degree of deformation is increased, the grain boundaries are increased and thereby making further slippage or deformation more difficult (Bolton, 1988). Hence, the 16 mm sample (relatively coarse grains) has better hardenability and machinability due to fewer grains boundaries present (Courtney, 1990). Since the toughness property is highly sensitive to change in grain size, hence, the smaller the grains, the tougher the sample becomes (Novikov, 1978).

Therefore, for applications (HTMT) that require adequate mechanical properties, a large degree of deformation should be employed.

REFERENCES

Askeland, R.D., 1994. The Science and Engineering of Materials. 3rd Edn., Boston pp: 79-81, 238-243.

Bolton, 1988. Production Technology-Processes, Materials and Planning. Heinemann London, pp: 174-185.

Courtney, T.H., 1990. Mechanical Behavior of Materials. McGraw Hill, London, pp: 309-312.

Dahl, W. and H. Rees, 1974. Symposium on Metallic Fracture Workshop.

Embury, J.D., 1975. Strengthening Methods in Crystals. Applied Science Publisher Ltd., London, pp: 67.

Hurley, P.J, B.C Muddle and P.D. Hodgson, 2000. Proc Thermomechanical Processing of Steels 2000. 24-26 May 2000. London pp: 476.

Hurley, P.J. and P.D. Hodgson, 2001. Materials Science and Engineering. A302: 206.

Kamma, C.M., 1990. Optimum conditions for grain refinement in carbon steels by thermo mechanical treatment. J. Mat. Forum, 14: 142-146.

Lakhtin, Y.M., 1990. Engineering Physical Metallurgy and Heat Treatment. 4th Edn., Moscow, pp: 252-256.

Llewellyn D.T., 1992. Steels: Metallurgy and Application. 1st Edn., Butterworth Heinemann, Oxford, pp: 64 -77.

Novikov, L., 1978. Theory of Heat Treatment of Metals. 1st Edn., Moscow pp: 105 -106; 418 -425.

Prasad, Y.U.R., 1975. Grain boundaries in Engineering materials proceeding. 4th Bolton Landing conference. Claytons Publication Division, pp: 67.