HIGH PRESSURE TORSION AND ITS APPLICATION FOR GRAIN REFINEMENT IN MEDIUM CARBON STEEL

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Abstract

Using the high pressure torsion (HPT) deformation method the medium carbon steel (AISI 1045) was an experimental material to conduct deformation process. The torsion deformation experiment was performed at increased temperature of 400 °C. The influence of deformation processing parameters, i.e. resolved shear strain γ (number of turns N= 1- 6) and applied pressure p (constant pressure of 7 GPa), were evaluated by microstructure analysis and mechanical properties of deformed specimens. The strength behaviour was assessed by microhardness measurements across the disc, by tensile tests and by in-situ measured torque. To obtain values of strength the ultimate tensile strength was measured in radial direction with respect to the deformed sample. The hardness value, measured at disc edge, was gradually increasing as shear stress increases. However, the hardness values at edge were different from those measured in disc centre and for applied straining no saturation were reached across the disc. The SEM and TEM investigations were carried out to analyze the microstructure evolution with respect to strain introduced. In order to evaluate the effect of the strain size on deformed structure evolution, which is supposed to change with turn numbers, the microstructure analysis was performed at edge and central site of the deformed discs. TEM investigation confirmed formation of new small grains applying the first turn, heterogeneity in fragmentation and dissolution of the cementite lamellae, the alignment of the fragments to the shear plane with acceding deformation and only small changes in microstructure deformation in the central part of deformed disc, regardless the strain introduced. Indistinctive deformation of ferrite at centre of disc and preserved cementite lamellae morphology were found at the centre of the disc.

1. INTRODUCTION

During the recent decade, bulk nanostructured materials produced by severe plastic deformation (SPD) have been investigated intensively. The production of fine grained materials by SPD, leads to a large number of investigations focusing on the substructure development and related mechanical properties. It has been already well known that SPD of metallic materials, involving processes such as equal angular pressing (ECAP), accumulative roll bonding (ARB) and high pressure torsion (HPT) is capable of producing ultrafine grained (UFG) materials with submicrometer or nanometer grain size [1, 2]. The wide range of results available for various materials deformed by HPT confirmed a saturation in microstructural refinement and the strength and hardness as strain increases [3, 4]. The results point out that there are differences in the development of the microstructure between the pure and multiphase steels [5, 6].

In this work two phase medium carbon steel has been deformed at increased temperature of 400°C by high pressure torsion to different strain (executing different numbers of turns) at hydrostatic pressure of 7 GPa.
The underlying relationship between microstructure and mechanical properties was analyzed with respect to the local axial position of analyses on the deformed disc.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

A commercial medium carbon steel (Fe-0.45%C, 0.42%Mn, 0.23%Si 0.18%Cr, 0.043%Al in wt. %) was supplied in form of rod with a diameter of 20 mm. Prior HPT deformation the steel was the annealed for 1.5 h at temperature of 850°C followed by air cooling in order to obtain uniform normalized structure. The mixture of quite coarse ferrite-pearlite structure was obtained as showed in SEM micrograph in Fig. 1. Following the annealing treatment, the size of pearlite colonies was of of ~ 30 μm and of ~ 15 μm was size of ferrite grains. The discs of 8 mm in diameter and ~ 0.95 mm in thickness have been cut of from rod and deformed by torsion up to 6 turns at temperature of 400 °C and a pressure of 7 GPa. The equivalent von Mises strain as a function of the number of turns \( n \) was calculated according to the relation: \( n = \varepsilon_{eq} = \frac{2\pi nr}{t} \sqrt{3} \). The size of effective strain conducting N- 1, 2, 4, and 6 turns was \( \varepsilon_{eq} \sim 15, 30, 60 \) and 90. The changes in mechanical properties in dependence on straining (number of turns) were determined by microhardness measurement across the deformed disc with a load of 300 g using Vickers mikrohardness tester, by static tensile test using subsize tensile pieces cut off at discs periphery (in radial direction) and by in-situ measurement of the torque. The reliable and accurate possibility to measure the torque during deformation allowed quickly to determine changes in mechanical strength without applying other method afterwards.

2. EXPERIMENTAL RESULTS AND DISCUSSION

Investigating material comprised of the coarse ferrite-pearlite steel AISI 1045, as shown in Figure 1. Using HPT method or refining coarse steel structure to nanostructure size needs the application of large strain, usually with an equivalent strain \( \varepsilon_{eq} \) more than 10. Electron microscopy analysis of thin foils prepared from deformed discs exposed to different strain revealed formation of various structural characteristic in dependence of strain applied and selected localization on the disc.

2.1. Microstructure analysis results

In order to compare the size of torsion straining at different position of deformed disc, Figure 2 shows the microstructure observed in steel after exposure to the first turn at temperature of 400°C. Finishing the first turn (\( \varepsilon_{eq} \sim 15 \)) the heterogeneity in structure development was still evident across the disc. At disc periphery alignment of smeared (partially dissolved) lamellae in pearlite next to the area of banded subgrain-like structure is documented in Figures 2 a, b. In the centre in the centre of the disc the lamellae remained, but some dissolution of the cementite lamellae, can be observed with smeared-like features, as presented in Fig. 2 c. Conducting 4 and 6 turns (\( \varepsilon_{eq} \sim 60 \) and ~ 90), the dual phase structure was significantly modified with respect to analysis site as presented in Figure 3. Regardless the strain size, successfully refined structure with small grains (grain size about of ~ 200 nm) having random high angle orientation was found in disc edge area as presented in Figure 3a. Selected area diffraction method (SAED) confirmed high angle disorientation of small grains. In the centre of the disc the structure has moderately deformed features. In
ferrite grains tangled dislocations are present, and pearlite colonies were only slightly deformed and/or locally fragmented, Figure 3b,c. From the TEM micrographs cementite lamellae thinning in central disc area is evident in structure. This fact is attributed to partial dissolution of cementite during shearing and results in decreasing of the lamellae thickness.

Fig. 2. TEM micrographs of microstructures observed at disc periphery after conducting the first turn (a & b), and corresponding to the centre of disc (c) experienced the $\varepsilon_{eq} \sim 15$.

Fig. 3. TEM micrographs of deformed microstructures conducting $N = 4$ turns found at periphery and at the centre of disc experienced the $\varepsilon_{eq} \sim 60$: a) edge; b, c) centre.

2.2 Mechanical properties

In order to characterize the changes in mechanical properties due to the large shear deformation the various methods were applied. Local Vickers microhardness and tensile properties were evaluated at room temperature. The torque, which was measured, contains next to the torque necessary to deform the sample solely a contribution from the region of the burr as well [5].

Microhardness measurements after different deformation exposure of specimens was the quickest and the most available method to estimate the mechanical strength of deformed specimens and is often used in order to provide a quick respond to applied different shear deformation in the [6, 7]. In present microhardness development after different deformation exposure was the quickest and the most easily available method to estimate the mechanical strength and is often applied in the literature [6,7]. In present work, this experimental method was mainly used to determine the change of the strength across the disc (at disc periphery and in the centre) after application of different $\varepsilon_{eq}$ and compared with hardness of the initial
The measured Vickers hardness (HV30) records for different number of turns are stated in Table 1. The results show some effect of softening appeared in disc after the fourth turn regardless the position, what can result from ultrafine grained structure dominancy and some dynamic recovery of dislocation structure in ferrite grains at disc centre. To obtain mechanical strength values, the specimens for tensile tests were machined out of HPT samples [8]. Two specimens (see in fig. 4) from each deformed disc were cut off from the deformed disc. Tensile behaviour was evaluated at room temperature and results in form of stress and elongation are documented in Figure 4. The ultimate strength was increasing with applied shear strain and maximum value obtained was higher than 1700 MPa.

The development of the ultimate tensile strength is similar to the in-situ measured torque. The records of in-situ measured torque curves for turn’s number of N1 and N6 are presented in Fig. 5. The possible explanation could be behind that the onset of steady state coincidences with saturation in the decrease of the grain structure size and tensile test data. The strain necessary to reach this deformation state depends on the materials structural state.

High pressure torsion method at increased temperature of 400°C was applied to refine microstructure in AISI 1045 steel. In dependence of strain applied there are markedly differences in the development of the microstructure as regards the site of analysis. Grain refinement and cementite lamellae dissolution was observed after the first turn ($\varepsilon_{eq} \sim 15$) at disc periphery. In disc centre, the deformed structure of ferrite with dislocation tangles had moderately

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* hardness of initial state of steel after annealing
deformed features of coarse cementite lamellae in pearlite grains. At higher strain applied cementite lamellae are directionally aligned, thinner and fragmented in dependence of the strain introduced. The effective strain increases, set probably equilibrium between the fragmentation cementite phase and new grains restoration processes and led to saturation of the refinement process. Upon tensile properties, the yield strength and ultimate strength increased with increasing $\varepsilon_{eq}$. A small decrease in the hardness across the disc was measured after execution of 4 turns, which may be related to formation of ultrafine grain structure in the disc but more probably due to only dislocation structure recovery in disc centre and preservation of initial structure.

SUMMARY

Severe plastic deformation of medium carbon steel AISI 1045 by high pressure torsion process produced ultrafine grained structure at periphery of the disc already after finishing the first turn. With strain increasing the ultrafine grain structure was formed and replaced the bimodal ferrite and pearlite microstructure. Structure heterogeneity was evident across the disc regardless the strain increased with number of turns from $N = 1$ to $N = 6$ when the effective strain $\varepsilon_{eq}$ reached value of $\sim 90$. The dissolution of cementite lamellae was contributing to their thinning. The fragmentation and alignment of cementite into the shear direction was accompanied by a hardness increase. Tensile tests records confirmed that ultimate strength increased with increasing shear strain and maximum value of $\sim 1700$ MPa was reach after performing $N = 6$ turns. The torque measurements during the deformation confirmed strong hardening in in deformed steel matrix at the beginning, whereas saturation behaviour for higher strain, as number of turns increased, was observed.

ACKNOWLEDGEMENT

This work was supported by the research project MSM 2631891901, financed by the Ministry of Education, Youth and Sports of the Czech Republic. Authors of the present work also gratefully acknowledge the support from the Erich-Schmid-Institute of Materials Science of the Academy of Sciences in Leoben, Austria.

REFERENCES