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Original Article

An overview of flow patterns development on disc lower surfaces when processing by high-pressure torsion☆

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ABSTRACT

Stainless steel was selected to study the flow patterns developed with anvil misalignments of 100, 200 and 300 μm on the disc lower surfaces during processing by high-pressure torsion (HPT) through totals of up to 16 turns. A pair of anvils having a roughness of Ra ≈ 15 μm was utilized to investigate the flow pattern development. Discs subjected to only compression in HPT exhibit similar characteristics to the as-received material in the phase domains and there were no overall curvatures of the austenitic (γ) and ferritic (α) phases. Double-swirl flow patterns were not observed in the 1 turn sample but they appeared on the disc lower surfaces after 5 and 16 turns with all three-anvil alignment conditions. There was no significant difference in the double-swirl configuration size for the 5 and 16 turns samples with different amounts of anvil misalignments. These results have important implications for processing metals by HPT.

1. Introduction

High-pressure torsion (HPT) is now recognized as the most effective severe plastic deformation (SPD) technique for producing ultrafine-grained and nanocrystalline metallic materials having superior mechanical properties including high strength [1–3]. During HPT processing, a disc is placed between two anvils and a torsional strain is imposed on the disc by applying a very high pressure (normally several GPa) to the upper anvil and simultaneously rotating the lower anvil. The shear strain imposed on the disc is estimated by the following equation based on the conventional rigid-body analysis [4]:

$$\gamma = \frac{2\pi Nr}{h} \quad (1)$$

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where r and h are the radius and height (or thickness) of the disc, respectively, and N is the number of revolutions. Based on the rigid-body assumption in Eq. (1), it is reasonable to anticipate that the strain is inhomogeneous in HPT and varies linearly from zero strain at the disc centre to a maximum at the outer edge of the disc. However, there is an additional strain on the HPT disc due to the applied compressive stress introduced in HPT processing and this compression stress is not considered in Eq. (1). This means that the real shear strain distribution during HPT processing is not well described.

Experiments show that a fully homogeneous microstructure and mechanical properties may be achieved in many materials after HPT processing [5–11]. The evolution towards microstructural homogeneity in HPT has been explained successfully by making use of strain gradient plasticity modelling [12]. Attempts have been made to understand the shear process and shear strain distribution during HPT processing through microstructural observations on a duplex stainless steel [13–15] and a two-phase Cu-Ag alloy [16]. Evidence of unusual flow patterns, including the occurrence of double-swirls and local vortices, provide a clear demonstration that flow within the disc is not always consistent with the anticipated rigid-body analysis. A possible explanation for these effects may lie in an initial misalignment of the anvils in the HPT facility prior to conducting the HPT processing [17,18]. However, no specific information on the initial anvil alignment was available in these earlier reports and no checks were undertaken to determine whether the anvils were in full alignment [13–16].

Later, the flow pattern development on the disc upper surfaces was studied systematically while using smooth anvils (with roughness of Ra ≈ 5 μm) under different amounts of anvil misalignment (specifically, 100 and 200 μm misalignment) [19–22]. It was found that double-swirls develop on the disc upper surfaces when processing by HPT with a controlled amount of misalignment of either 100 or 200 μm in the anvil positions but there were no double-swirls when processing with essentially perfect alignment. Measurements showed the separations between the centres of the double-swirls both increased with increasing anvil misalignment and decreased with increasing numbers of turns [19]. Furthermore, if the straining was continued to a sufficiently large number of turns, as with 16 turns for an anvil misalignment of 100 μm, the double-swirl pattern disappeared [19,22].

Recently there was the first report on the effect of the initial anvil roughness on the flow patterns [23]. By comparing the flow patterns developed on the disc upper and lower surfaces using both rough and smooth anvils with a fixed anvil misalignment of 100 μm, it was shown that there were some differences in the flow patterns, which were dependent upon the initial surface roughness. However, there was no systematic investigation of the flow pattern development while using the rough anvils under different amounts of anvil misalignment. Therefore, the present research was undertaken in order to study the flow patterns generated on the disc lower surfaces when using rough anvils with a series of initial anvil misalignments of 100, 200 and 300 μm.

2. Experimental material and procedures

A commercial F53 super duplex stainless steel was obtained from Castle Metals UK Ltd. (Blackburn, Lancashire, UK) with a chemical composition consisting of C < 0.030, Si < 0.80, Mn < 1.20, P < 0.035, S < 0.020, Ni 6.0–8.0, Cr 24.0–26.0, Mo 3.0–5.0 and N 0.24–0.32 (wt.%). Fig. 1 shows the as-received microstructure which consists of essentially equal proportions, and similar volume fractions, of the lighter-contrast austenitic (γ) and the darker-contrast ferritic (α) phases. The widths of these two phases varied between ~5 and ~50 μm. Since the two phases exhibit good contrast, this material provides an excellent opportunity to reveal the flow patterns that are introduced during processing by HPT.

The as-received material was in the form of a rolled plate having a thickness of 3 mm. Disks having diameters of ~9.8 mm and thicknesses of ~1.2 mm were cut from the plate and then ground carefully to give a uniform thickness of ~0.82 mm. Processing by HPT was conducted at room temperature under quasi-constrained conditions in which a small amount of material flows outwards around the periphery during the processing operation [24,25]. During HPT processing, the upper anvil is in a fixed position and the lower anvil rotates in a single direction. Any parallel shift between the axis of the upper anvil and the axis of the lower anvil is designated as a measure of the anvil misalignment between the upper and lower anvils. The present experiments were conducted by making changes in the anvil alignment prior to HPT processing. Three different anvil alignment conditions were utilized in these experiments by making a deliberate parallel shifting of the upper anvil: the anvil misalignments were (1) about 100 μm, (2) about 200 μm and (3) about 300 μm. Normally the anvil alignment would fall within <100 μm when processing materials in a conventional manner. Therefore, an anvil misalignment of ~300 μm is rather large and is almost visible by eye observations. Nevertheless, an anvil misalignment of 300 μm was included in order to have systematic observations

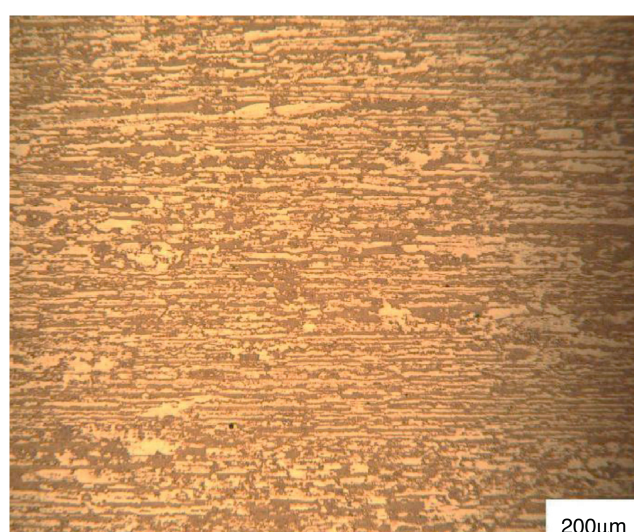

Fig. 1 – Microstructure of the as-received duplex stainless steel.