Ultrafine-Grained Stainless Steels after Severe Plastic Deformation

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Both mechanical properties and corrosion resistance of various stainless steels can be optimized owing to grain refinement decreasing the grain size down to hundreds of nanometers. The ultrafine-grained (UFG) microstructures can be obtained in ferritic and austenitic stainless steels by means of large strain deformation using severe plastic deformation (SPD) or conventional processing methods under conditions of cold to warm working. The UFG stainless steels are characterized by high strength. However, the strengthening by large strain deformation is accompanied by a substantial degradation of plasticity. Therefore, the UFG stainless steels are frequently subjected to recovery/recrystallization annealing to balance the strength and plasticity. The revealed relationships among a range of microstructural parameters open up a promising approach to clarify the mechanical behaviour of UFG stainless steels. Therefore, UFG stainless steels produced by large strain deformation have great potential for various applications as structural and functional materials.

Keywords: stainless steels ; ultrafine-grained microstructures ; severe plastic deformation ; grain refinement ; work hardening ; recovery and recrystallization ; strength and plasticity

1. Introduction

Currently, stainless steels with ultrafine-grained (UFG) microstructures are considered as promising materials for certain applications, when corrosion resistance combined with improved mechanical properties such as high strength and sufficient ductility along with enhanced impact toughness is required [1][2][3][4][5][6][7][8][9]. Commonly, recrystallization is applied to control the developed microstructures in bulky metallic materials [10]. Of particular importance is dynamic recrystallization (DRX) resulting in the desired grain size directly during plastic deformation [11][12][13][14][15]. The main regularities of DRX have been fairly clarified in a number of papers [16][17][18][19][20]. The DRX grain size decreases with a decrease in deformation temperature and/or an increase in strain rate. Therefore, the substantial grain refinement can be obtained through plastic deformation at relatively low temperatures. However, the strain, which is required for the DRX development, increases significantly with a decrease in the processing temperature. Therefore, one of the recent approaches to produce ultrafine-grained stainless steels involves severe plastic deformation (SPD), which is actually large strain (or redundant strain) deformation at relatively low temperatures [21][22][23]. Typical strains imposed by SPD vary in a very large range, depending on material and processing conditions. The strain corresponding to steady-state deformation behavior can be considered as a sufficiently large one.

A number of specific processing methods have been developed to date to impose large strains on processed material at low to moderate temperatures [4][21][24][25][26][27][28]. It should be noted that large strain deformation can be also achieved by some conventional metal-forming methods such as drawing and rolling. The latter ones are simple in utilization and can be applied by using ordinary equipment. Recently, rolling, swaging, and forging have been successfully applied to process several ultrafine-grained stainless steels [29][30][31].

2. Large-Strain Processing

Renewed about 50 years ago, interest in large-strain processing, i.e., SPD, was motivated by two achievements. Those are the obtained ultrafine-grained and nanocrystalline metals and alloys with reportedly outstanding properties [32] and the success in application of special SPD methods [4]. One of the most frequently used SPD methods is torsion under hydrostatic pressure (HPT) which was adapted from the Bridgeman anvil [33][34]. The sample as a thin disc is subjected to torsion around the disc axis using the friction provided by the large hydrostatic pressure of about 5 GPa (**Figure 1**a). Equivalent strains well above 100 that may lead to a nanocrystalline microstructure in various metallic materials can be applied with HPT [34][35]. A disadvantage of HPT is associated with a limitation of the process within a small-scale laboratory investigation.

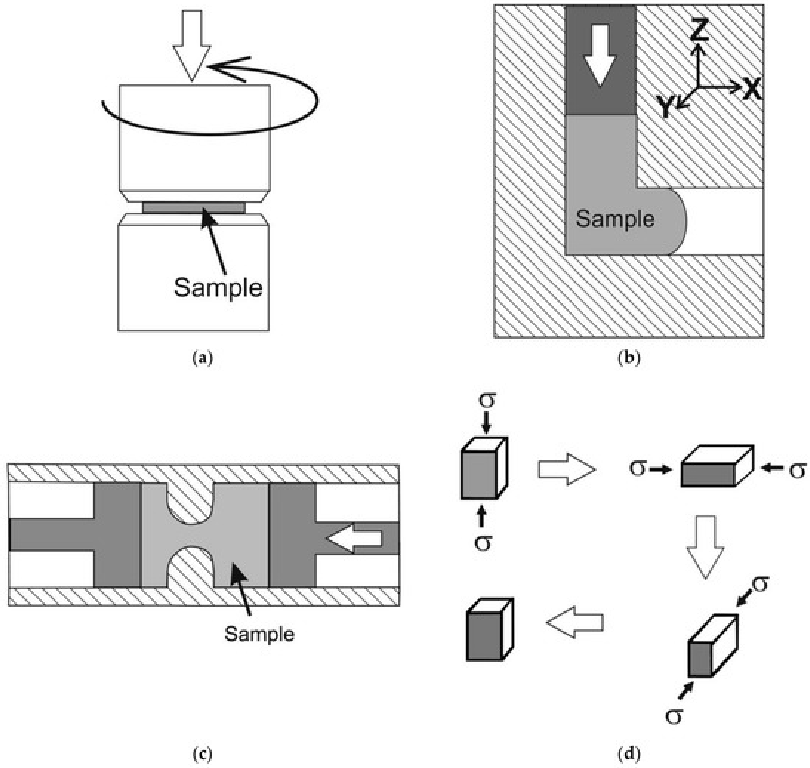

Figure 1. Large strain deformation by high-pressure torsion (HPT) (**a**), equal-channel angular pressing (ECAP) (**b**), reciprocating extrusion (**c**), and multiple multidirectional forging (**d**).

Following the principles outlined by Segal et al. [36], another SPD method, i.e., equal-channel angular pressing (ECAP) was developed and successfully applied for processing rather ductile materials [21][37] (**Figure 1**b). During ECAP, the sample is pressed in a closed die with two equal-sized channels intersecting at an angle of φ resulting in a strain of γ = 2 cot φ/2 [21]. In the case of a number (N) of sequential ECAP passes, the strains are commonly summed, and an equivalent strain can be defined as follows [36]: $\varepsilon = (2N/\sqrt{3}) \cot \varphi/2$. Compared to HPT, ECAP requires costly equipment and cannot be applied for materials with limited ductility, although ECAP combined with the CONFORM process [38] can be used for sizeable samples.

A number of well-known conventional metal-forming techniques also allow obtaining very large strains. Many industrial processing methods such as rolling, drawing, and swaging can be also used for large strain deformation [39] leading to UFG evolution in various metals and alloys. These methods are quite easy to utilize because they can be carried out using standard tools. It should be noted that certain dimensions of the processed sample are continuously reduced during deformation. This drawback limits the practical application of unidirectional processing methods such as SPD for producing UFG structural materials. On the other hand, the same drawback stimulates investigations dealing with the control of the UFG evolution kinetics to obtain the desired UFG microstructure in bulky products suitable for practical applications after reasonable strains.

There are several methods of large strain deformations retaining the original shape of the processed sample without substantial changes. Those are commonly cyclic in realization and based on reversing the strain path for each cycle, providing redundant deformation with reversible change in the shape of the processed sample [21]. Among those, reversing extrusion [25] and multiple forging [40] seem to be the most effective and elaborated (**Figure 1**c,d). The former provides very large strains for constrained samples, although some difficulties maybe experienced in processing hard-to-deform materials. Multiple forging is one of the simplest and most easily realized methods, accumulating large total strain in the samples with sufficient plasticity. The total strain can be estimated by a summation of the strain in each forging pass, i.e., $\varepsilon = \ln (H_i/H_f)$, where Hi and Hf are the initial and final heights of the sample. In contrast to other SPD techniques, multiple forging (sometimes called ABC forging [41]) allows obtaining the relationship between true stress and true strain, which is very important for understanding the microstructure–property relations [42][43]. Besides the SPD techniques mentioned above, there are many other specific SPD methods that should also be noted, such as accumulative roll-bonding [44], friction stir processing [45], continuous cyclic bending [46], repetitive corrugation and straightening [47], mechanical milling [48][49], and hydrostatic extrusion [50] and its modification for long-scale samples [51].

3. Ultrafine-Grained Microstructures

UFG steels and alloys are those with a grain size of less than 1 μm [52]. Moreover, UFG microstructures developed by SPD involve high dislocation density in the form of cell walls and sub-boundaries [14]. Such a mixture of fine grains/cells/subgrains with large internal distortions complicates the microstructural investigations of UFG materials. Usually, UFG microstructures are studied by means of transmission electron microscopy (TEM). High-resolution TEM reveals fine details of deformation microstructures, including the mutual arrangement of strain-induced boundaries/sub-boundaries and lattice dislocations, although arduous specimen preparation and limited observation area consume a lot of researchers' time and energy.

Recently, the powerful technique of orientation imaging microscopy (OIM) based on the automatic analysis of Kikuchi patterns from backscattered electrons in a scanning electron microscope has been developed and introduced for comprehensive microstructural analysis [53]. OIM consists in the systematic measurement of the crystallographic orientation on the surface of the sample section from point to point throughout the arbitrarily selected area. The resulting maps of the distribution of orientations open up great opportunities for microstructural analysis [54]. The results obtained make it possible to reveal the boundaries of grains/subgrains and their characteristics. OIM allows characterizing the spectrum of misorientations, which is one of the most important characteristics of the deformation microstructure. Since OIM maps can include up to several tens of thousands of grains/subgrains, large statistics can also be included in the key advantages of this method. Regarding crystallographic textures, OIM may well compete with X-ray diffraction. The benefits of OIM include a wide choice of treating the data, which can be represented as any (at the user's choice) pole figure or orientation distribution function [54]. The rapid development of OIM over the past few decades makes it possible to successfully use OIM for studying even very complex structures, such as nanocrystalline [55][56] and severely deformed [57][58] structures. Therefore, OIM will be given preference when available while considering the UFG microstructures developed in stainless steels subjected to SPD.

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