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Extreme grain refinement by severe plastic deformation: A wealth of challenging science

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Abstract

This article presents our take on the area of bulk ultrafine-grained materials produced by severe plastic deformation (SPD). Over the last decades, research activities in this area have grown enormously and have produced interesting results, which we summarise in this concise review. This paper is intended as an introduction to the field for the "uninitiated", while at the same time highlighting some polemic issues that may be of interest to those specialising in bulk nanomaterials produced by SPD. A brief overview of the available SPD technologies is given, along with a summary of unusual mechanical, physical and other properties achievable by SPD processing. The challenges this research is facing—some of them generic and some specific to the nanoSPD area—are identified and discussed.

Keywords: Severe plastic deformation; Ultrafine-grained materials; Modelling; Properties

1. Historical overview

Grain size can be regarded as a key microstructural factor affecting nearly all aspects of the physical and mechanical behaviour of polycrystalline metals as well as their chemical and biochemical response to the surrounding media. Hence, control over grain size has long been recognized as a way to design materials with desired properties. Most of the mentioned properties benefit greatly from grain size reduction. As the race for better materials performance is never ending, attempts to develop viable techniques for microstructure refinement continue. A possible avenue for microstructure refinement of metals is the use of severe plastic deformation (SPD)—a principle that is as old as metalworking itself. Recent essays [1–4] tell a fascinating story of the art of ancient swordmaking through SPD. The modern-day history of SPD technology has its beginnings in the seminal work by P.W. Bridgman who developed the scientific grounds and techniques for materials processing through a combination of high hydrostatic pressure and shear deformation [5,6], which today are at the core of SPD methods. Bridgman effectively introduced the defining characteristics of SPD processing in the early 1950s. In a strict sense generally accepted in the materials engineering community, an SPD process is currently defined as "any method of metal forming under an extensive hydrostatic pressure that may be used to impose a very high strain on a bulk solid without the introduction of any significant change in the overall dimensions of the sample and having the ability to produce exceptional grain refinement" [7]. In this Diamond Jubilee issue of *Acta Materialia* it is appropriate to mention that many of the modern ideas of thermomechanical processing involved in virtually all SPD schemes were already addressed in the first volume of *Acta Metallurgica* in 1953. Carreker and Hibbard [8] pointed out that the yield strength of high-purity copper benefits substantially from grain refinement and this effect is more pronounced at low temperatures. They also noticed that the effect of the initial grain size vanishes at strains larger than 0.1 and for that reason the grain size has little or no influence on the strength under monotonic loading. A

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similar effect is well known in fatigue where the grain size of wavy-slip materials has no bearing on the fatigue limit. These observations can be associated with the vital role of the dislocation substructure, which forms during deformation (be it monotonic or cyclic), and it is the size of the substructure which determines the strength characteristics of metallic materials. Gow and Cahn [9] emphasized the significance of crystallographic texture for the deformation and recrystallization behaviour of metals and the effect of evolving texture on the resultant properties. Bell and Cahn [10] outlined many fine features of mechanical twinning, which play an important part in plastic deformation when accommodation by dislocation slip is hindered. Beck [11] highlighted the possibility of relieving the work-hardening effects by post-processing recovery. As will be seen in the following sections, these ideas have had a great impact on the development of the SPD processing and are pivotal to the modern concepts underlying these techniques. Nowadays, the subject of SPD processing is represented very prominently on the pages of *Acta*, as illustrated by the analysis in Ref. [4]. Its revival is due to the work of Segal et al. [12] in the Soviet Union in the mid-1970s. These authors developed the method of equal-channel angular pressing (ECAP), which later evolved into what is now the most popular SPD technique. It should be mentioned, however, that in the time between the publication of Bridgman's studies and the reintroduction of this subject in the metal science literature, exploration of the possibilities of changing the properties of materials through combined high pressure and shear deformation went on both in the Soviet Union and in the West. This less known work has been reviewed in Ref. [13]. In particular, credit should be given to the work by the group of N.S. Enikolopian conducted mainly on polymers.

A real appreciation for the new possibilities for improving the properties of metallic materials provided by SPD techniques came with the work of the group of Valiev [14,15], which demonstrated the relation between the enhanced strength and the extreme grain refinement imparted by SPD processing to a range of metals and alloys. The seminal work of this group, emphasizing the great potential of SPD processing with regard to property improvement through grain structure modification, has heralded what has been described as the "microstructural age" of SPD research [4]. Over the last decade, the nanoSPD community (www.nanospd.org) has grown to an impressive group of researchers, and thousands of publications on ultrafine-grained (UFG) and nanostructured materials produced by SPD have been published. It is probably not surprising that in the year of the Diamond Jubilee of this journal, the Acta Materialia Gold Medal goes to Professor Terry Langdon—one of the world leaders in the area of nanoSPD materials. A representative collection of the relevant articles on the subject can be found in the proceedings of symposia on UFG materials [16,18] and nanoSPD conferences [19,20]—the most recent ones in a series of five such forums. Further useful sources include the reviews [21,22] and special issues of *Advanced Engineering Materials* [23], *Materials Science and Engineering A* [24] and *Materials Transactions* [25,26].

What makes SPD processing techniques so popular is the possibility of using them to enhance the strength characteristics of conventional metallic materials in a quite spectacular way: by a factor of up to eight for pure metals such as copper and by some 30–50% for alloys [7,27]. Despite the impressive property improvement achievable with SPD techniques, their uptake by industry has been rather sluggish. However, things are now starting to change, and there is a common feeling in the nanoSPD community that major breakthroughs in terms of industry-scale applications of SPD-based technologies are imminent. We have been working in this area for more than a decade and have followed its developments closely. In this article we present our views on what has been achieved, what is possibly achievable, and what future trends are to be expected from SPD processing technologies. This article does not represent a full review of the SPD area (one could almost say the discipline of SPD, considering the firm place this group of material processing techniques has taken in literature). Rather, it is our personal take on the SPD area and an attempt to foretell its future development. Emphasis is placed on the scientifically challenging aspects of SPD, and not so much on technological issues, although some insights into the promises and limitations of SPD technologies will also be given.

2. SPD methods

Among the procedures devised for grain refinement, SPD techniques are of particular interest and are the focus of the present review. These techniques enjoy great popularity owing to their ability to produce considerable grain refinement in fully dense, bulk-scale work-pieces, thus giving promise for structural applications. The achievable grain sizes lie within the submicrometer (100–1000 nm) and nanometer (<100 nm) ranges. SPD-processed materials with such grain sizes are generally referred to as nanoSPD materials [7], although only the latter ones can be regarded as being nanostructured according to the conventional definition. Several comprehensive reviews have focused on various nanoSPD processing techniques [22,28–33]. We refer the reader to the original works for specific details and only briefly outline the general SPD methodology underlining the common features and the most important differences between the nanoSPD processes. By no means do we claim that our list of currently available manufacturing schemes is exhaustive.

After the landmark work by Bridgman mentioned above [6,34], Langford and Cohen [35] and Rack and Cohen [36] demonstrated in the 1960s that the microstructure of Fe–0.003% C subjected to high strains by wire drawing was refined to subgrain sizes in the 200–500 nm range. These microstructures could not be regarded as UFG proper in