

THE CURRENT STATUS OF BULK NANOSTRUCTURED MATERIALS

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Abstract. Although the science of bulk nanostructured materials (BNM) has a relatively short history, extending through only about the last two decades, these materials are becoming of increasing importance in modern Materials Science. By analyzing data from four major scientific journals, it is shown that papers on BNM and associated topics represent almost 50% of the all-time top ten most cited publications.

1. INTRODUCTION

The term “bulk nanostructured materials” (BNM) refers to materials with ultrafine grain sizes that may be produced through the application of severe plastic deformation (SPD) to bulk coarse-grained solids. Formal definitions of the various terms in this research field were given in an earlier publication [1] but it is important to note two specific definitions.

First, processing by SPD refers to “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.” Second, bulk ultrafine-grained materials are defined as “bulk materials having fairly homogeneous and equiaxed microstructures with average grain sizes less than $\sim 1 \mu\text{m}$ and with a majority of boundaries having large angles of misorientation.”

Examples of representative SPD processing techniques are Equal-Channel Angular Pressing (ECAP) where a rod or bar is pressed through a die

constrained within a channel which is bent through an abrupt angle [2], High-Pressure Torsion (HPT) where a disk is subjected to a high pressure and concurrent torsional straining [3] and Accumulative Roll-Bonding (ARB) where a sheet is rolled, cut into two halves, stacked and rolled again through a repetitive cycle [4].

2. AN HISTORICAL APPROACH TO BNM

Although SPD processing is a relatively new and attractive tool within the field of modern Materials Science, the principles of SPD processing have an extremely long history. Thus, the fundamental technology was first used in ancient China, during the Han dynasty around 200 BC and the Three States dynasty of 280 AD, when local artisans developed a new and effective forging technique for the fabrication of high-strength steels for use as swords [5]. A repetitive forging and folding procedure was introduced to harden the material and this principle forms the basis for the famous Bai-Lian steels. In fact, evidence suggests this process may have been

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Table 1. Journals used in the evaluation.

Journal	Total number of published papers	Impact Factor
<i>Progress in Materials Science</i>	346	16.579
<i>Acta Materialia</i>	8338	3.781
<i>Scripta Materialia</i>	8209	2.806
<i>Materials Science and Engineering A</i>	21,341	2.090

Table 2. All-time ranking for *Progress in Materials Science*.

Ranking	Author(s)	Year	Volume and page	Topic	Number of citations	Reference
1	Valiev <i>et al.</i>	2000	45 , 103	SPD	2238	[15]
2	Gleiter	1989	33 , 223	NANO	2224	[16]
7	Valiev and Langdon	2006	51 , 881	SPD/ECAP	699	[2]
9	Meyers <i>et al.</i>	2006	51 , 427	NANO/SPD	598	[17]

developed as early as about 500 BC. Ultimately, the principles of this process spread to Japan and then to India where it led to the development of a special ultra-high carbon steel known as Wootz steel [6] and to Syria where it was adopted in the processing of the famous Damascus steel [7].

All of this early work was conducted with no knowledge or understanding of fundamental scientific principles but this approach changed in the 1930's and 1940's when Nobel Laureate P.W. Bridgman, working at Harvard University in the United States, introduced a scientific approach into the processing of bulk solids through the use of a hydrostatic pressure [8,9]. Later work in the former Soviet Union, most notably led by Valiev and his colleagues in Ufa a little over twenty years ago [10,11], introduced a microscopic capability to the evaluation of the bulk materials produced by SPD processing and this approach subsequently became very important for fully characterizing these new and advanced materials.

The preceding brief review shows that the scientific development of SPD processing and the production of bulk nanostructured materials extend over a relatively short time span of only about twenty years. This is much shorter than other major research fields within Materials Science such as, for example, mechanical testing or phase transformations. It is appropriate, therefore, to consider the current status of BNM and specifically to examine the impact of research in this area within the broad domain of Materials Science. Earlier reports examined this impact both on a universal level [12,13]

and with special emphasis on the many scientific achievements produced through research in Ufa [14]. The current paper is designed to provide an update on the global significance of BNM.

3. CURRENT STATUS OF BNM: IMPACT IN THE SCIENTIFIC LITERATURE

For the purposes of this analysis, all data are taken from the ISI Web of Science website where ISI is The Institute for Scientific Information in Philadelphia, PA, USA. The numbers on this website change on a daily basis and the analysis presented here corresponds to information recorded in the second week of September, 2011, shortly after the BNM-2011 conference in Ufa. In practice, the numbers will be a little higher at the time of publication of this report but nevertheless the overall rankings will remain very similar to those reported here. Therefore, this report gives a good summary of the status of BNM and SPD processing as of the latter part of 2011.

In order to obtain an overall impression of the impact of SPD research on the scientific literature within the discipline of Materials Science, it is appropriate to consider four major journals which receive and publish a significant fraction of the research in this field. These journals are listed in Table 1 together with the all-time total numbers of papers published within each journal and the journal Impact Factor which provides information on the status and overall quality of the publication. The first listed jour-

Table 3. All-time ranking for *Acta Materialia*.

Ranking	Author(s)	Year	Volume and page	Topic	Number of citations	Reference
2	Gleiter	2000	48 , 1	NANO	1022	[18]
3	Iwahashi <i>et al.</i>	1998	46 , 3317	SPD/ECAP	651	[19]
4	Kumar <i>et al.</i>	2003	51 , 5743	NANO	609	[20]
5	Saito <i>et al.</i>	1999	47 , 579	SPD/ARB	600	[21]
6	Iwahashi <i>et al.</i>	1997	45 , 4733	SPD/ECAP	543	[22]

Table 4. All-time ranking for *Scripta Materialia*.

Ranking	Author(s)	Year	Volume and page	Topic	Number of citations	Reference
1	Iwahashi <i>et al.</i>	1996	35 , 1431	SPD/ECAP	876	[23]
2	Saito <i>et al.</i>	1998	39 , 1221	SPD/ARB	395	[4]
4	Mukai <i>et al.</i>	1997	36 , 69	SPD/ECAP	320	[24]
6	Tsuji <i>et al.</i>	2002	47 , 893	SPD/ARB	287	[25]
9	Tsuji <i>et al.</i>	1999	40 , 795	SPD/ARB	237	[26]

Table 5. All-time ranking for *Materials Science and Engineering A*.

Ranking	Author(s)	Year	Volume and page	Topic	Number of citations	Reference
1	Segal	1995	A197 , 157	SPD/ECAP	1160	[27]
3	Valiev <i>et al.</i>	1998	A168 , 141	SPD	733	[11]
4	Valiev <i>et al.</i>	1991	A137 , 35	SPD	585	[10]
5	Furukawa <i>et al.</i>	1998	A257 , 328	SPD/ECAP	572	[28]
10	Birringer	1989	A117 , 37	NANO	338	[29]

nal, *Progress in Materials Science*, only publishes fairly long review articles so that the total numbers of papers is relatively small and yet the Impact Factor is exceptionally high. The other three journals, *Acta Materialia*, *Scripta Materialia* and *Materials Science and Engineering A*, are regular scientific journals publishing submitted papers that describe new developments within the broad field of Materials Science including within the BNM/SPD area.

For each journal, the ISI Web of Science was used to examine the all-time top ten most cited papers over the life-time of the journal. It is important to note that the top ten papers represent an exceptionally small subset of the total numbers of papers published in each journal: for example, it corresponds to about 3% of the total papers published in *Progress in Materials Science* and very much smaller fractions in the other three journals. Using the published data for each journal, those

papers were selected which relate specifically either to SPD, where the specific areas were denoted in terms of the processes of ECAP, HPT and ARB, and the more general field of nanostructured materials which is henceforth designated NANO.

The results of analyzing the website data are shown in Tables 2 to 5 for *Progress in Materials Science*, *Acta Materialia*, *Scripta Materialia* and *Materials Science and Engineering A*, respectively. In each Table, the individual ranking within the top-ten papers is given in the column on the left, the second column lists the author(s), the third column gives the year of publication, the volume and page number are given in the fourth column, the fifth column defines the topic of each selected paper, the sixth column summarizes the precise numbers of citations for each selected paper and the seventh and final column gives the reference.

Inspection of Tables 2 to 5 shows that the impact of BNM on the discipline of Materials Science has been quite remarkable. Papers within this field, covering both SPD and NANO, represent four of the all-time top ten most-cited papers in *Progress in Materials Science* and an additional five papers in each of the other three journals. This means that BNM represents 19 out of 40, or close to 50%, of the all-time top ten most cited papers in these four major journals. Furthermore, the listing includes the top two most cited papers in *Progress in Materials Science*, the second, third, fourth, fifth and sixth most cited papers in *Acta Materialia*, the top two most cited papers in *Scripta Materialia* and the top most cited paper in *Materials Science and Engineering A*. This analysis provides conclusive proof that BNM has had a very major impact on modern Materials Science.

4. SUMMARY AND CONCLUSIONS

The processing of nanostructured materials has a long history that precedes the introduction of scientific rigor and understanding. By contrast, the scientific approach to these materials is a relatively new aspect of the discipline of Materials Science. Nevertheless, the impact of this topic has been immense. Papers on nanostructured materials and processing through the application of severe plastic deformation now represent almost 50% of the top ten all-time most cited papers within four of the major journals in Materials Science. In view of the current interest in this research area, it seems probable that this impact will continue and may even expand as new major developments are reported in the scientific literature.

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