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Nanostructuring in powder metallurgy and forging technologies

Nanostruktury w metalurgii proszków i technologiach kucia

Abstract
In recent years, near-nano (submicron) and nanostructured materials have attracted more and more attention from the materials community. Nanocrystalline materials are characterized by a microstructural length or grain size of up to about 100 nm. Materials having grain size of 0.1-0.3 mm are classified as submicron materials. Nanocrystalline materials possess unique mechanical properties. When the grain size is below a critical value (10–20 nm), more than 50% (by volume) of atoms is associated with grain boundaries or interfacial boundaries. In this respect, dislocation pile-ups cannot form, and the Hall–Petch relationship for conventional coarse-grained materials is no longer valid. Therefore, grain boundaries play a major role in the structure formation of nanocrystalline materials. Nanocrystalline materials exhibit creep and super plasticity at lower temperatures than conventional micro-grained counterparts. In this review paper, current developments in fabrication, microstructure, physical and mechanical properties of nanocrystalline and submicron materials made by Powder Metallurgy and Forging techniques will be addressed. Particular attention is paid to the properties characterization of submicron composites.

Streszczenie
W ostatnich latach coraz większym zainteresowaniem materiałoznawców cieszą się materiały prawie nanostrukturalne (submikronowe) i nanostrukturalne. Materiały nanokrystaliczne charakteryzują się mikrostrukturalną długością i wielkością ziaren do 100 nm. Materiały o wielkości ziarna 0,1–0,3 mm klasyfikowane są jako materiały submikronowe. Materiały nanokrystaliczne posiadają unikalne własności mechaniczne. Gdy wielkość ziarna jest poniżej wartości krytycznej (10-20 nm), ponad 50% (objętościowo) atomów związanych jest z granicami ziaren lub granicami międzyfazowymi. W tej sytuacji nie mogą powstawać nawarstwienia dyslokacyjne i zależność Hall–Petch obowiązująca dla konwencjonalnych materiałów gruboziarnistych nie ma już zastosowania. Zatem, granice ziaren odgrywają ważną rolę w tworzeniu struktury materiałów nanokrystalicznych. Materiały nanokrystaliczne wykazują pełzanie i nadplastyczność w niższych temperaturach niż ich konwencjonalne odpowiedniki mikroziarniste. W tym przeglądzie kierujemy uwagę na bieżące postępy w wytwarzaniu: mikrostrukturę, własności fizyczne i mechaniczne materiałów nanokrystalicznych wytwarzanych technikami metalurgii proszków i kucia. Szczególną uwagę zwraca się w tej pracy na własności kompozytów submikronowych

Key words: powder metallurgy, nanocristalline material, nanostructure, composite, property

Słowa kluczowe*: metalurgia proszków, materiał nanokrystaliczny, nanostruktura, kompozyt, własność*

1. INTRODUCTION

Nanomaterials are experiencing a rapid development in recent years due to their applications in a wide variety of industry areas such as electronics, catalysis, ceramics, magnetic data storage, structural components etc. To meet the technological demands in these areas, the size of the materials should be reduced to the nanometer scale. As the size reduces into the nanometer range, the materials exhibit peculiar and interesting mechanical and physical properties, e.g. increased mechanical strength, enhanced diffusivity, higher specific heat and electrical resistivity compared to conventional coarse grained counterparts [1]. Nanomaterials can be classified into nanocrystalline materials and nanoparticles. The former

are polycrystalline bulk materials with grain sizes in the nanometer range (less than 100 nm), while the latter refers to ultrafine dispersive particles with diameters below 100 nm. Nanoparticles are generally considered as the building blocks of bulk nanocrystalline materials [2]. Nanomaterials and most of the applications derived from them are still in an early stage of technical development. There are several issues that remain to be addressed before nanomaterials will become potentially useful for industrial sectors. These issues include synthesis of materials, characterization of new structures and properties of nanophase materials, fabrication of dense products from nanoparticles with full density and less contamination, and retention of the ultrafine grain size in service in order to preserve the mechanical properties associated with the nanometer scale.

The unique properties of nanocrystalline materials are derived from their large number of grain boundaries compared to coarse-grained polycrystalline counterpartes. In nanocrystalline solids, a large fraction of atoms (up to 49%) are boundary atoms [2]. Thus the interface structure plays an important role in determining the physical and mechanical properties of nanocrystalline materials. Nanocrystalline metals have been found to exhibit creep and superplasticity with high strain rates at lower temperatures than their micro-grained counterparts. High strain-rate superplasticity at lower temperatures is of practical interest because it can offer an efficiently near-net-shape forming technique to industrial sectors [2]. Despite recent advances in the development of nanocrystalline materials, much work remains to be done to achieve a basic understanding of their deformation and fracture behavior. When the grain size is below 20 nm, strength appears to decrease with further grain refinement. At this stage, dislocation sources inside the grains can hardly exists. This implies that dislocation pile-ups cannot form and the Hall–Petch relationship for conventional coarser grained materials is no longer valid. Several mechanisms have been proposed to explain the anomalous deformation behavior of nanocrystalline materials with the grain size below the critical value [2]. These include grain boundary sliding, grain-boundary diffusion, the triple junction effect, etc. Therefore, comprehensive understanding of the processing-structure property relationships is essential in the development of novel nanomaterials with unique properties for structural engineering applications.

While there are a number of bulk properties that may be dramatically changed when the microstructure is nanoscale, this paper focuses on the review of technologies of nanostructured materials and results obtained in Metal Forming Institute last time. These are (1) the Powder Metallurgy and (2) Forging (deformation) of nanostructured materials for a variety of potential tribology and structural applications.

2. PROCESSING NANOCRYSTALLINE MATERIALS

Nanocrystalline materials are the issue of numerous research in recent decades, thousands papers are being published at the last time (see reviews [1-5]) since landmark Gleiter review [3]. Nanocrystalline materials are single- or multi-phase materials organized in units having dimensions in nanometer range ($1x10^{-9}$-$200x10^{-9}$). These units (submicron and nanograins) can be structured in one, two, or three dimensions. At the lower end of this spectrum are amorphous materials (glasses) [4].

Processing of bulk nanostructured materials is being accomplished by either the ‘‘bottom-up’’ assembly of atoms or molecules into nanoscale clusters which require subsequent consolidation into bulk material, or the ‘‘top-down’’ methods which start with a bulk solid and obtain a nanostructure by structural decomposition. The bottom-up methods include the inert gas condensation, powder synthesis and compaction techniques. While the bottom-up methods were used to make the nanocrystalline materials for early studies of its’ properties, they suffer from both the limited size of material that can be prepared and from the common problem of two-step methods in that the compaction (consolidation)step may not provide completely dense or bonded mate-

rial in spite of improvements to the process [1]. Electrodeposition can be classified as a ‘‘bottom-up’’ method of preparation of nanocrystalline materials and also as ‘‘one-step’’ since no consolidation step is needed. Thick electrodeposits may be considered to be bulk materials. Since the late 1980s electrodeposition has been studied as a method to produce nanocrystalline materials and it has moved into the commercial production of such materials [1]. The ball milling of powders- mechanical attrition has been a popular method to produce materials with a nanocrystalline grain size [5]. The ball milling of powders can be divided into two categories: (1) the milling of elemental or compound powders (“mechanical milling”), and (2) the milling of dissimilar powders (“mechanical alloying”), in which material transfer occurs. This subject has been reviewed by a number of authors [6,7,17].

Most consolidation methods have used pressure assisted sintering approaches. Shear stresses are most effective in collapsing pores and also disrupt surface oxide layers. Since deformation processes which have significant shear stress components are desired Koch [1] lists the processes in order of decreasing effectiveness as follows: extrusion—sinterforging—uniaxial hot pressing—hot isostatic pressing (HIP). Non-conventional consolidation methods for densification of nanocrystalline particulates include microwave sintering, field assisted sintering methods, and shockwave consolidation.

The possibility of producing very fine grain structures by severe plastic deformation (“top-down” approach) was suggested by research using conventional deformation methods with high strains. It has been known for many decades, going back to the 1950s, that the structure of deformed metals is being altered with a plastic deformation by the way of random dislocation arrays transformation into into “cells” or “subgrains” such that there is a high dislocation density in the cell walls and a lower dislocation density within the cells. In most cases, the early studies of microstructures produced by severe plastic deformation gave cell or subgrain sizes in the micron down to submicron size scale, but not into the nanoscale. In recent years special methods of deformation have been developed for producing submicron and even nanoscale grains with high angle grain boundaries.

These methods, the microstructure developed, and the properties of the materials with the refined grains so produced have been reviewed by Valiev et al. [8]. The major methods of severe plastic deformation, in addition to mechanical attrition, are severe plastic torsion straining under high pressure (HPT) and equal channel angular pressing (ECAP). In the case of HPT a disk shaped sample is compressed to pressures of about 2 GPa to 6 GPa and then one of the dies is moved with respect to the other. With enough rotation very large values of strain can be achieved, well into the 100s. This method has been used to achieve submicron grain sizes and in some cases even nanocrystalline grain sizes. The ECAP method which allows for the deformation of a various rods by pure shear was first developed by Segal [9]. In this method a billet is pressed through a die with two channels at angles of intersection typically 90^{o} to 120^{o}. The billet is subjected to severe deformations without changing its dimensions. Multiple passes through the die provide accumulative strain. The grain sizes developed by this method are typically in the submicron range (200-300 nm).

There are examples of submicron size grain structures induced by the severe strain of ECAP in several metals that provide an excellent combination of both increased strength along with good ductility [8,9]. However, As shown by Segal [9], for effective processing from practical point of view, ECAE should be optimized for many characteristics. The optimal balance corresponds to minimum contact friction, tool angle 90, sharp corner channels and square long or flat billets. During multipass ECAE, the process optimization for particular problems should also include the corresponding choice of route with minimum number of passes [9]. The elimination of contact friction along a bottom wall of the second channel is especially important. Tool design with movable walls provides a control of contact friction and stable processing. Possible areas for commercialization of ECAE may include both ordinary and unique industrial applications.

Koch [1] stated that the total strain provided by a given deformation process is in large part responsible for the final grain size that can be obtained. This must be a function of the dislocation density that can be obtained and its subsequent rearrangement by thermal processes. The processes that can provide the highest practical strain levels would be HPT, ECAE and mechanical attrition of powders. Mechanical attrition typically results in a powder product which then requires consolidation. The processing challenge is to produce nanocrystalline materials with the finest grain sizes to maximize strength, but without defects that might compromise ductility. Thus, development of the extrusion-sinter forging-uniaxial hot pressing-HIP, and microwave sintering, field assisted sintering methods, and shockwave consolidation seems to be of great importance.

3. STRUCTURE AND PROPERTIES OF NANOCRYSTALLINE MATERIALS

A main structure characteristic of the nanocrystalline materials is the grain size. As shown in reviews [1, 3,7,11] the minimum grain size achieved by various processing steps depends on a number of process and material variables. The most effective technology from this viewpoint is high energy milling or mechanical alloying [10]. The minimum grain size is shown to depend on a balance between the defect/dislocation structure introduced by the plastic deformation of milling and its recovery by thermal processes (Figure 1) [1]. The power and exponential approximations of the dependence $d = d\,(1/T)$ reveal about the competition between defect creation and removal processes, and just for the higher melting metals it is obvious that high energy milling can produce fine grain sizes below 10 nm. However, in order to attain bulk material, the powders need to be consolidated. The ability to maintain the very small grain sizes in as-milled material and obtain bulk nanocrystalline material with minimal grain growth remains a challenge [1].

FCC nanocrystalline metals (Ni, Cu, Fe, Ti) processed by SPD, are characterized with a high level of internal distortions within a nanosized grain body, which increase with approaching the grain boundary, and a non-equilibrium state of grain boundaries attributed to high dislocation density (see review [11]). Nanocrystalline Mo and W processed by SPD have "wider" grain boundary interlayers with high dislocation density than FCC metals [11], which is most likely due to low dislocation mobility in BCC metals.

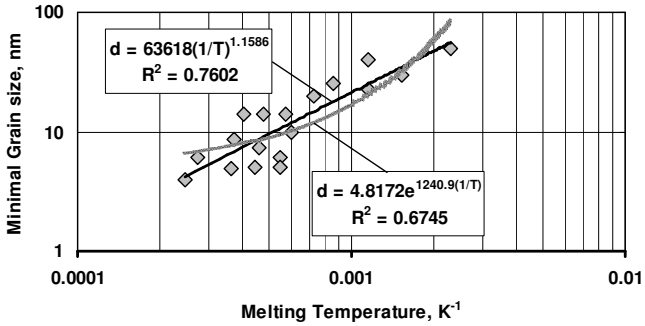


Fig. 1. Minimum nanograin size for ball milled powders after Koch [1]

Rys. 1. Minimalna wielkość nanoziaren dla mielonych proszków kulkowych według Koch [1]

Mechanical properties of nanocrystalline materials are determined mainly by the nanograin size d and the state of nanograin boundaries. The experimental results [11] reveal that with decreasing d from 1500 to 5 nm the microhardness H of pure metals may increase by a factor of 2-6 in accordance to Hall-Petch law. The yield strength $\sigma_{0.2}$ and ultimate tensile strength σ_B of nanocrystalline metals also grow compared to those of the coarse grain state, while the low temperature plasticity δ decreases (Table 1).

The deviation from the Hall-Petch law for nanograin sizes to be result of change of the deformation mechanism in the fine nanocrystalline materials [4]. As an illustration of grain size influence on mechanical properties of nanocrystalline multiphase alloys the data of work [11] are presented in the Table 2.

Table 1. Microhardness (*H*), yield strength ($\sigma_{0.2}$) and ultimate tensile strength (σ_B) of pure metals with different grain size (*d*) processed by SPD (after Noskova[11])
Tablica 1. Mikrotwardość (H), umowna granica plastyczności ($\sigma_{0.2}$) i wytrzymałość na rozciąganie (σ_B) czystych metali o różnej wielkości ziaren (d) obrobionych metodą SPD (według Noskova [11])

Metal	***d* change, nm (from-to)**	***H* change, GPa (from-to)**	**$\sigma_{0.2}$ change, MPa, (from-to)**	**σ_B change MPa (from-to)**	**Δ change, % (from-to)**
Ti	500000-40	0.8-6.7	275-980	420-1310	29-5
Fe	10000-80	1.8-4.5	375-1010	480-1100	25-15
Cr	1500-70	-	313-780	485-960	-
Al	1500-200	0.3-1.2	13-26	42-176	20-2
Mo	500-50	1.0-6.0	-	-	-
W	200-40	3.0-6.2	-	-	-
Cu	200-70	0.9-1.4	60-365	120-650	60-30
Cu	70-20	1.4-1.8	-	-	-

Table 2. Nanograin size (*d*), microhardness (*H*), yield strength ($\sigma_{0.2}$), ultimate tensile strength (σ_B) and relative elongation (δ) of coarse-crystalline and nanocrystalline alloys processed by SPD (after Noskova [11])
Tablica 2. Wielkość nanoziaren (d), umowna granica plastyczności ($\sigma_{0.2}$), wytrzymałość na rozciąganie (σ_B) i wydłużenie względne (δ) grubo-krystalicznych i nanokrystalicznych stopów obrabianych metodą SPD (według Noskowa [11])

Alloy	***d* change, nm (from-to)**	***H* change, GPa (from-to)**	**$\sigma_{0.2}$ change, MPa (from-to)**	**σ_B change, MPa (from-to)**	**δ change, % (from-to)**
FeCuNbSiB	200-6	6.0-15.0	140-2180	140-2280	0-0.8
CoFeSiB	100-25-25-8	10.5-13.0-13.0-9.0	945-1880	950-2100	0-2.6
VT-6	120000-40	-	950-1080	1050-1350	9-7
Fe-12%Cr-18%Ni-10%Ti	3000-150	-	500-1600	-	-
Fe-12%Cr-25%Ti	2000-50	1.8-6.5	-	1500-2500	-
AlNiCeFe	2000-80	-	-	120-1560	-
Al-10%Mg	2500-900	0.3-0.5	120-170	180-275	0.5-1.1
Al-1%Re	2000-440	0.3-0.6	30-150	35-180	-
Al-1%Hf	2500-760	0.3-0.4	30-160	40-180	
Al-1%Hf-0.2%Nb-0.2%Sn	2000-110-110-60	0.4-0.8-0.8-1.8	40-140	60-200	0.3-4.8
Al-0.5%Ce-0.5%Re-0.1%Zr	2000-150-120-40	0.4-0.65-1.0-1.9	40-180	80-220	0.1-5.2
AlMgLiZr	500-20	-	-	490-680	-
Ni_3Al	1000-60	-	-	780-3000	-

It is seen that in alloys, similar to pure metals, the transition to a structure with sub-micro- or nanosized grains is accompanied by the increase in microhardness and strength. Besides, there is observed an increase in plasticity in the alloys in the state of superplasticity at high temperatures. Similar to pure nanocrystalline metals, the Hall-Petch dependence for nanophase alloys is valid not within the whole nanophase size range [1,3,4,11]. In most cases the Hall-Petch law is not valid for alloys with a grain size of 30 nm and less, the coefficient k having a negative value. The possible causes for violation of the Hall-Petch law for nanocrystalline alloys are the same as for pure metals, namely, modification of the plastic deformation mechanism and the weakening of nanograin boundaries.

The analysis of data of the Tables 1, 2 is shown on Figure 2. The effect of alloying on the properties of ultrafine grain Al alloys is clearly seen. The multicomponent alloying Al results in increase of the SPD effectiveness. The similar results were described in [12]. In this work high-purity aluminum alloys with selected contents of magnesium have been in-

vestigated with respect to microstructure and mechanical properties before and after SPD. For comparison, a commercial aluminum alloy has also been used. With increasing amounts of alloying elements, the microstructure after ECAP becomes finer, and the dislocation density inside the ultrafine grains is higher. Only in high-purity aluminum the formation of a submicron microstructure is difficult, because the lack of impurities promotes dynamic recovery and recrystallization during the ECAP process. In the ultrafine-grained condition, the hardness of all other alloys (Table 2) is increased by a factor of about 3 in comparison to their recrystallized counterpart. A strong improvement of the fatigue properties by introducing a submicron microstructure was found [12].

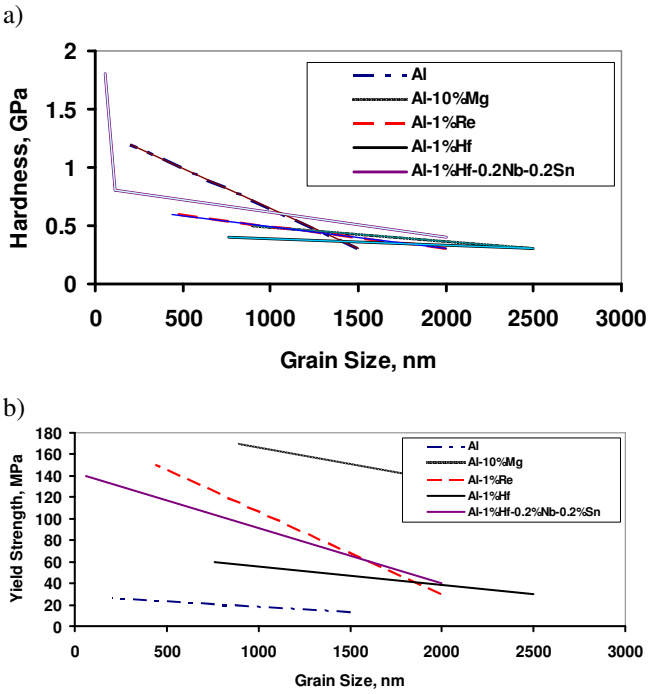


Fig. 2. Effect of the grain size on Hardness (a) and Yield Strength (b) for Al and Al alloys (the data of Table 1, 2 [11])

Rys. 2. Wpływ wielkości ziarna na twardość (a) i umowną granicę plastyczności (b) dla Al i stopów Al (dane z tablicy 1, 2 [11])

The outstanding mechanical and physical properties of nanocrystalline materials and their high propensity for enhanced diffusion even at low temperatures are caused by their structural characteristics including nanoscale structure and the extremely high volume fraction of grain boundaries [13]. Some above described results on mechanical characterization of materials with nanostructures look very promising, demonstrating potential for an attractive combination of strength and plasticity in such materials. A key obstacle in obtaining these advantageous properties is development of new Powder Metallurgy - Forging methods for synthesis of high-quality nanocrystalline materials free from porosity and contamination, and engineering design of structural features (for example, bimodal structures and grain boundary engineering [13,14]).

4. CHARACTERIZATION OF NANOCRYSTALLINE MATERIALS STRUCTURE

The main experimental methods of alloy structure characterization are the Field Emission Scanning Electron Microscopy (FESEM), High Resolution Transmission Electron Microscopy (HRTEM) and Scanning Probe (SPM) or Atomic Force Microscopy, and analysis of diffracted X-ray peaks (XRD), based on the X-ray peak width at half maximum or, preferably, the full X-ray peak shape. Determining the grain size is a rather critical point. The different techniques used lead to strongly diverging results, as the physical principles for sensing the grain boundaries differ. XRD yields the diameter d_X of coherently scattering spherical volume elements. It senses not only high, but also low local misorientations, even less than 2^o, related to low-angle boundaries and dislocation dipoles. TEM in general does not differentiate between low-angle and high-angle boundaries. TEM images are frequently evaluated by the line intersection technique to yield the grain size d_T as mean length of grain intercepts. SEM with backscattered electrons has been used to determine a grain size d_S ; in general SEM senses misorientations above a few degrees.

Phase Imaging is a powerful extension of SPM (Tapping Mode) that provides nanometer-scale information about surface structure and properties often not revealed by other AFM (SPM) techniques.

By mapping the phase of the cantilever oscillation during the Tapping Mode scan, phase im-

aging goes beyond simple topographical mapping to detect variations in composition, adhesion, friction, viscoelasticity, and numerous other properties. Figure 3 illustrates the possibilities of Phase Imaging SPM for grain structure characterization. The method allows to define the nanograin parameters for multiphase materials.

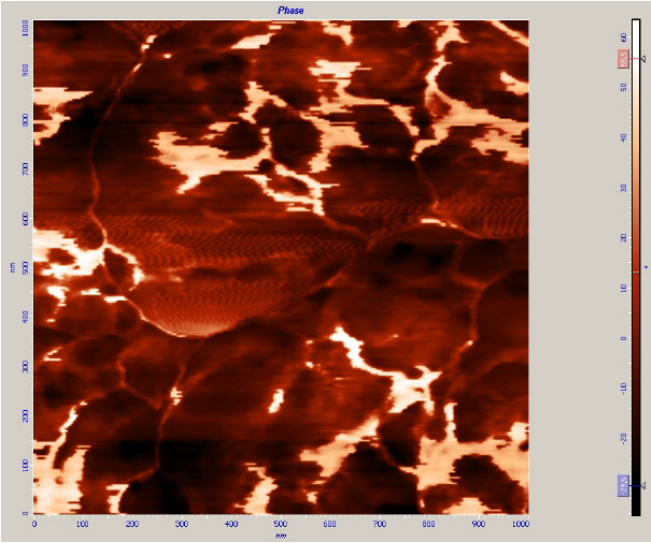


Fig. 3. Phase imaging with phase illumination of FeCu powder alloy structure
(SPM Solver P47-SPM-MDT)
Rys. 3. Struktura proszku stopu FeCu (SPM Solver P47-SPM-MTD)

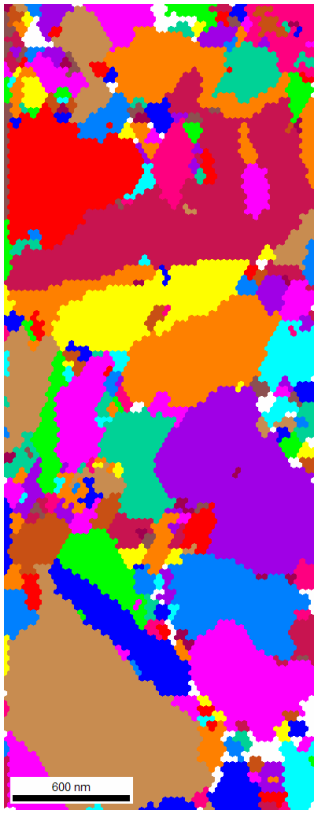
Applications of the Phase Imaging SPM include mapping of different components in composite materials, and differentiating regions of high and low surface adhesion or hardness. In many cases, phase imaging may be complemented with lateral force microscopy (LFM), and force modulation techniques, often providing additional information more rapidly and with higher resolution. One can note that only stiffness of an each phase plays the main role for SPM phase image reconstruction in this case.

For over a decade, electron backscatter diffraction (EBSD), an analytical technique in the scanning electron microscope, has demonstrated the ability to obtain precise crystallographic information from a microscopic region in a fraction of a second. Accordingly, an EBSD analysis can identify phases, grain texture, and plastic deformation in a variety of materials with unparalleled success, even at submicron levels. Several extensive reviews of EBSD that discuss the technique's capabilities exist [15], to which we refer the reader requiring background information. Presently, the highest demonstrated EBSD resolution is on the order of 10 nm, and indexing rates have reached more than 200 points per second, owing to recent improvements in field emission SEMs, CCD cameras, computer speed, and indexing algorithms [15]. The results of EBSD examination of submicron structure of SP 163 tool steel shown on Figure 4 reveal in detail the grain parameters. It is clearly seen that the grain size of heat treated S 163 sample varies in the wide range (Figure 4a,c) because of insufficient thermal stability of structure at the austenizing temperature 1120^{o}C. The regular SEM examination of the structure (Figure 4b) does not allow to define the grain structure in detail.

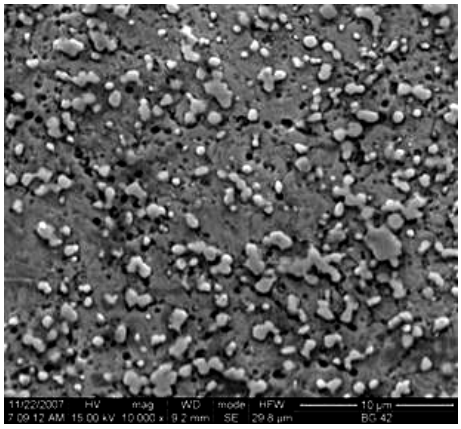
The thermal stability of nanocrystalline materials' structure is important for both technological and scientific reasons. From a technological point of view, the thermal stability is important for processing nanocrystalline materials without coarsening the microstructure. The grain growth of nanocrystalline microstructures is a criterion for allowing strategies for minimizing grain growth to be developed. Grain growth in nanocrystalline materials has been reviewed by and Koch [1], Suryanarayana [7], and oth. The thermal stability in a broader sense involves not only the stability of the grain structure, that is the microstructure, but also the stability of the structure of the grain boundaries in nanocrystalline materials. A number of investigations on the thermal stability of nanocrystalline materials have been conducted.

However, the lack of the real data of a heat treatment effect on the parameters of submicron and nanostructure does not allow to apply nanocrystalline materials. We have tried to evaluate the thermal stability of S 163 tool steel submicron structure during heat treatment by grain size measurement.

a)



b)



c)

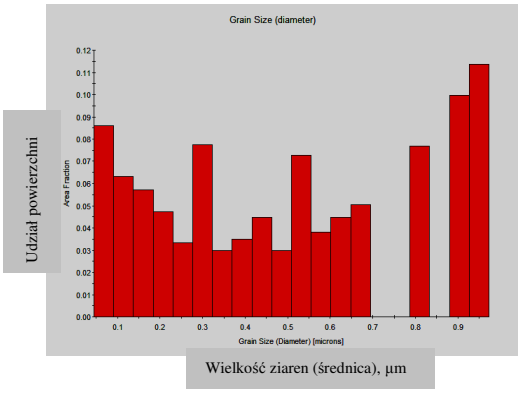


Fig. 4. EBSD analysis (a,c) and SEM image of SP 163 steel grain structure (b)

Rys. 4. Analiza EBSD(a,c) i obraz SEM struktury ziarnistej stali SP 163 (b)

The results the measurements are shown in Figure 5 as a dependence of the average grain size on austenizing temperature reciprocal. The exponential approximations of functions carbide size $d_C = d_C(1/T_A)$ and austenite grain size $d_A = d_A(1/T_A)$ shown on Figure 5 reveal about diffusion nature of the grain growh process. There are two basic ways in which grain growth can be reduced [1]. The first is the kinetic approach in which the grain boundaries are pinned in various ways to decrease grain boundary mobility. The second is the thermodynamic approach in which the driving force for grain growth is lowered by reducing the grain boundary energy. In the case of S163 tool steel the first approach may be realized due to careful choice of austenizing temperature.

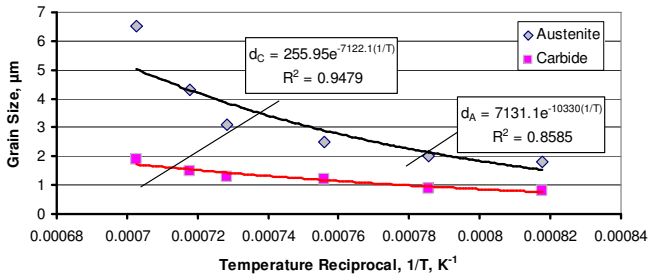


Fig. 5. S 163 tool steel average grain size after heat treatment at various austenizing temperatures

Rys. 5. Średnia wielkość ziaren stali narzędziowej S 163 po obróbce cieplnej w różnych temperaturach austenityzacji

In spite of the observation of abnormal grain growth (Figure 4a,c), even at very low homologous temperatures, significant stabilization of nanocrystalline grain structures has been observed. The content of submicron grains in the structure even at the austenizing temperature 1120°C is about 50% (Figure 4c).

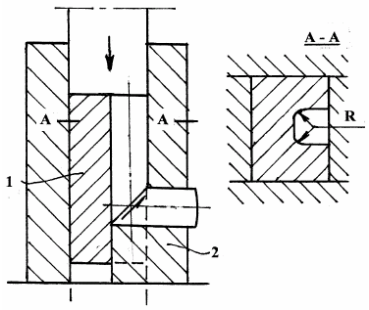
5. NANOCRYSTALLINE COMPONENT MANUFACTURING DEVELOPMENT

Based on previous discussion we have to note a mainstream of nanocrystalline components route is the combination of Powder Metallurgy (PM) and Powder Forging (PF) operations in order to achieve both nanocrystalline structure and precise dimensions of vari-

ous components. PM comprises several different technologies for fabricating semi-dense and fully dense components. The conventional PM process (press-and-sinter), the metal injection molding (MIM), hot isostatic pressing (HIP) may be used to produce nanocrystalline powder parts. The conventional press-and-sinter route is being extensively developed in INOP and the results of study are being implemented in INOP PM Pilot Plant which is producing now the first pilot batches of components with controlled nanostructure – sliding bearings and valve seats.

The special powder forging (PF) processes need to be developed to create nanocrystalline structure of particulate components. These technology will possess to achieve the severe deformation regimes for powder materials with the virgin nanostructure received due to previous PM operations. From this viewpoint development of SPD technologies for real nanocrystalline components is believed to be of great importance. One of the such technology is believed to be ECAE of powder performs with the tool with movable walls to prevent the negative effect of the friction forces [9]. The schemes of the tool are shown on Figure 6.

a)



b)

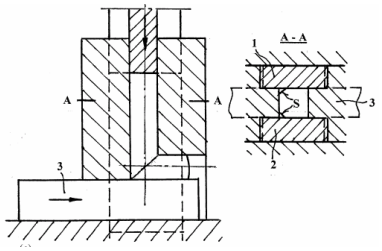


Fig. 6. ECAE tool design in accordance with Segal [9] : a - three movable walls into the first channel; b - two movable walls into the first channel and movable bottom wall into the second channel

Rys. 6. Konstrukcja narzędzia ECAE według Regal [9]: a – trzy ruchome ściany w pierwszy kanał; b – dwie ruchome ściany w pierwszy kanał i ruchoma ściana dolna w drugi kanał

Orbital forming (rotary forging) is a specialty metal forming process which uses lower and upper dies set at an angle to form metal into required shapes. The orbital motion forces the metal to deform at a lower force level than other cold forming processes. Orbital forming (OF) seems to attractive technology to produce components of a complex shape with submicron grain structure. The OF technology was developed in United Kingdom, Russia, Germany and Poland. OF has responded to the new manufacturing demands in two ways. Machine manufacturers are recognizing that equipment costs need to be substantially reduced to attract new investment. Secondly, as an incremental process, OF is a slower means of manufacture than other traditional forging methods. In most applications it will be extremely difficult for OF to compete with the production times of conventional hammers and presses [18]. To overcome this, it is necessary for the process to produce high-value products that the conventional processes are unable to make. These include products that have high accuracy, complex net shape features (generally cold forged), fine grain structure (due to severe deformation) and/ or those that through design can eliminate individual products in an assembly. Since OF is often carried out cold on smaller, quieter machines, it offers ideal opportunities for incorporation of the OF in modern manufacturing facilities as an advanced severe deformation system.

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