MODERN METHODS IN POWDER METALLURGY OF ALLOYS, INTERMETALLICS AND COMPOSITES

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Abstract

Nowadays, powder metallurgy (PM) is used in many industrial applications. Conventional PM processes, such as cold pressing and sintering are used frequently in series production due to nearly waste-free use of initial materials and limited or no requirements on further processing by machining. However, these simple processes do not bring significant improvement of mechanical properties and also keep relatively high levels of residual porosity. In production of highly demanding materials, such as high-strength alloys, intermetallics or special composites, modern methods of powder metallurgy are under rapid development. Among powder metallurgy techniques used for powder production, mechanical alloying, which allows for the production of nanocrystalline alloys and intermetallics, composites or oxide dispersion strengthened (ODS) materials, plays very important role. Among the sintering methods, Spark Plasma Sintering (SPS) process became a leading tool because of extremely short sintering times, as well as reduced sintering temperature. Thanks to these facts, the unique properties of nanocrystalline powders can be preserved. Currently, there exist interesting variants of SPS, such as High Pressure SPS and hybrid devices combining SPS and induction heating. In production of intermetallics, there is also a possibility to use the Self-propagating High-temperature Synthesis (SHS) process. In these processes of reaction synthesis, energy is supplied to the compressed mixture of pure metallic powders or other precursors by heating or by electric discharge. In this paper, the applications of the above described methods are presented on aluminium alloys, titanium- and iron-based intermetallics and aluminide-ceramics composites.

Keywords: Powder metallurgy; mechanical alloying; spark plasma sintering; SHS

1. INTRODUCTION

Powder metallurgy started to be applied in 1950’s mainly due to the need to process high-melting metals and cemented carbides, which cannot be manufactured by the use of conventional melting metallurgy ways. The powder metallurgy technologies consist of two important steps - powder production and its consolidation to compact materials. Initially, the powders were produced by chemical reduction (e.g. tungsten from tungsten oxide) or by milling (hard materials, e.g., carbides). Among the consolidation techniques, the combination of cold pressing and subsequent sintering was applied in the first period of powder metallurgy use dominantly. After that, more efficient processes have been developed, enabling to obtain significantly improved properties also in the case of common materials as tool steels. Up to now, the combination of rapid solidification technique (melt atomization by inert gas) and hot isostatic pressing has been established as an industrial method for processing of highly alloyed tool steels (group of VANADIS steels) [1]. These materials are able to achieve better mechanical and tribological properties than common tool steels due to a significant structure refinement by rapid solidification. However, the ultrafine-grained structure achieved by melt atomization is not completely preserved during hot isostatic pressing due to a temperature-induced grain coarsening. Therefore, it is clear that special consolidation techniques are needed to process nanostructured powders. Also the powder production technologies underwent a huge development. This paper presents modern trends in powder production and consolidation technology, which can be applied in processing of metallic materials, i.e. alloys, intermetallics and metal-matrix composites.

2. POWDER PRODUCTION

Among powder production techniques, mechanical alloying, which allows for the production of nanocrystalline intermetallics, plays very important role. Mechanical alloying is a solid-state powder processing method, involving repeated welding, fracturing and re-welding of powder particles [2] during high-energy ball milling (**Figure 1**). This method produces ultrafine structures which are far from equilibrium state.

Mechanical alloying enables to achieve following materials attributes:

- production of fine dispersion of strengthening phase particles,
- extension of solubility limits,
- refinement of the grains down to nanometer scale,
- synthesis of metastable crystalline phases (e.g. quasicrystals [3]),
- formation of amorphous powders,
- alloying even by insoluble elements (e.g. Mg-Ti hydrogen storage alloys [4],
- low-temperature initiation of solid state reactions.

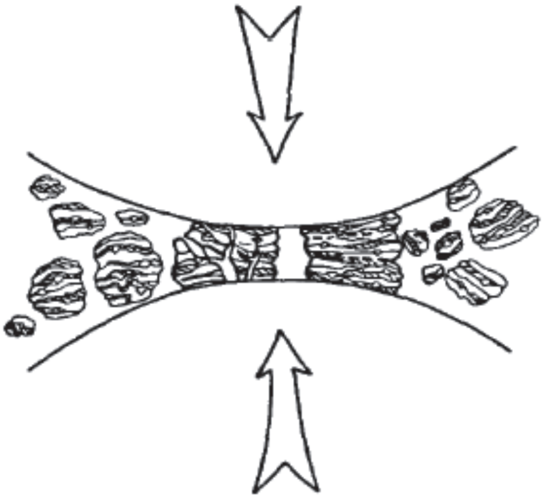

Figure 1 Schematic description of the mechanical alloying process [2]

Mechanical alloying was already practically applied for the synthesis of many kinds of intermetallics [5, 6, 7]. However, the process itself takes long time (up to 50 h), which is considered as its main disadvantage. During the research in previous years, the ultra-high energy mechanical alloying was developed by balancing the ball-to-powder ratio, rotational velocity and the milling environment. This method enables to obtain intermetallic phases quantitatively in 2-4 h of milling. This process was already applied for the synthesis of Al-Cu-Fe quasicrystals [3], the powders of Al-Si-Fe based alloys with high thermal stability and strength [8], Ni-Ti shape memory alloys [9] and also iron-based intermetallics (Fe-Al and Fe-Al-Si alloys).

3. POWDER CONSOLIDATION

Mechanical alloying produces ultrafine-grained powder that has to be consolidated to produce a bulk intermetallic phase. The number of applicable consolidation techniques is very limited in the case of intermetallics due to low plasticity and poor sinterability of the intermetallics' powders. In practice, hot isostatic pressing or Spark Plasma Sintering (SPS) are applicable. Spark Plasma Sintering, i.e. the consolidation by uniaxial pressing combined with the passage of pulsed electric current, seems to be the most promising technique due to low process duration and lower process temperature required. It prevents coarsening of the grains of intermetallics [3]. As examples of fine structure obtained by mechanical alloying and consequent spark plasma sintering, the Al-Si-Fe based alloy for elevated temperatures [8] and Fe-Al-Si intermetallic alloy are presented in **Figure 2**. The main disadvantage of SPS is a low pressure used during pressing/sintering due to the limitations of the graphite moulds. These disadvantages could be overcome by the use of High Pressure Spark Plasma Sintering (HP SPS) which allows for the use of the pressures up to 8 GPa [10].

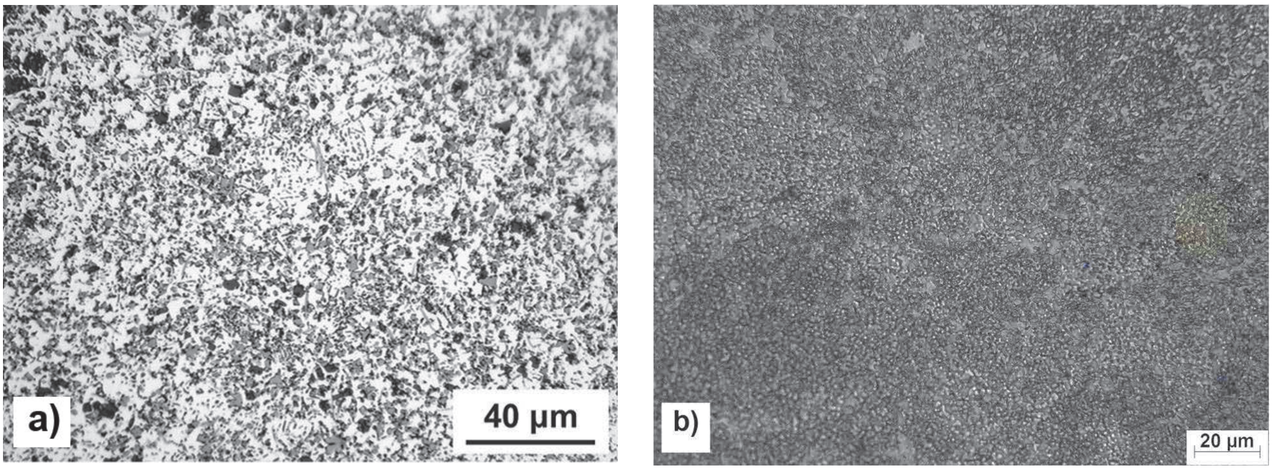

Figure 2 Microstructure of the products of mechanical alloying and spark plasma sintering:
a) Al-23Si-8Fe-1Cr alloy [8], b) Fe-20Al-20Si alloy

4. REACTIVE SINTERING

The specific group of methods can be called in general “reaction synthesis” or “reactive sintering”. These methods are especially suitable for the synthesis of intermetallics or in-situ composites. In these processes of reaction synthesis, energy is supplied to the compressed mixture of pure metallic powders or other precursors by heating or by electric discharge. Due to the exothermic nature of the reactions leading to the formation of intermetallics, the energy is necessary only for the initiation of the reactions (**Figure 3**). After that, heat produced by the reactions sustains and propagates the reaction towards the body of the reactants [11]. Due to this fact, the process is often called “Self-propagating High-temperature Synthesis” (SHS) [7].

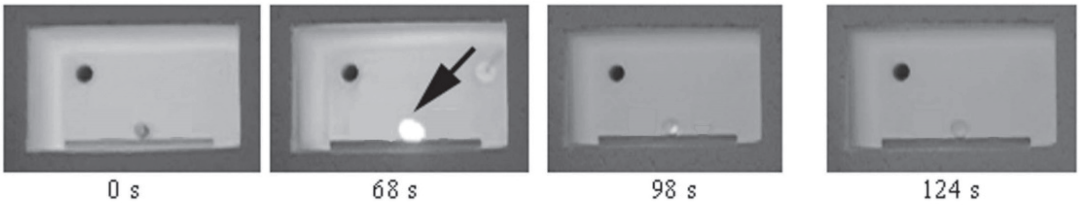

Figure 3 SHS progress in Ti-15Al-15Si powder mixture [11]

Reactive sintering is the simplest method for the manufacture of bulk intermetallics. However, in some systems (e.g. Fe-Al or Ti-Al) this process results in highly porous products [11]. The solution of this problem is the pressure-assisted reactive sintering. In some cases, reactive sintering or SHS in general can be applied for the synthesis of the materials with controlled porosity, such as NiTi scaffolds [12] or newly developed porous Ti-Si based alloys for bone substitution (**Figure 4**).

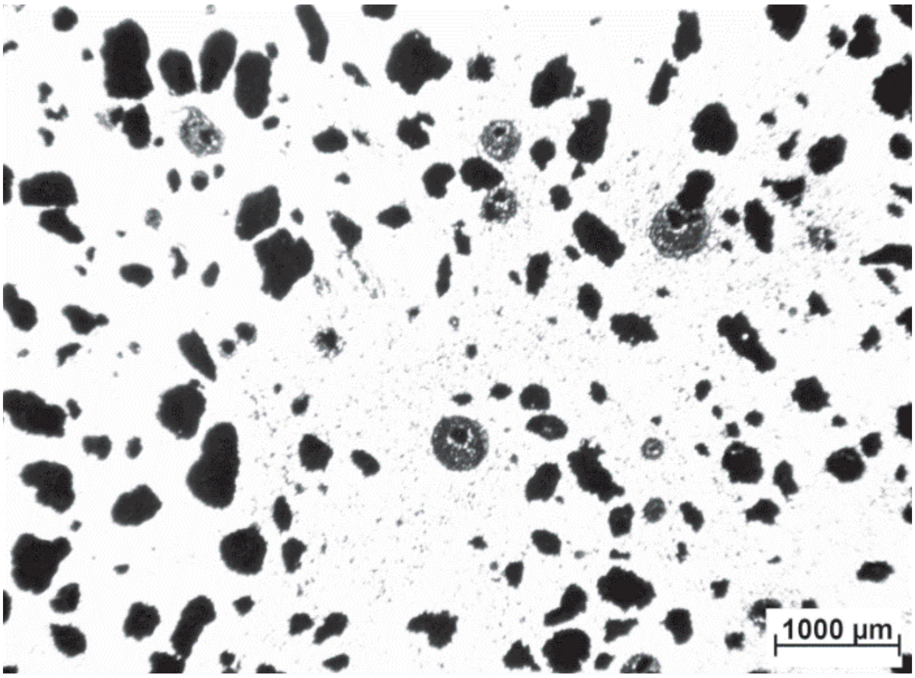

Figure 4 Structure of new titanium and silicon containing intermetallics-based biomaterial

Reactive sintering also allows the preparation of intermetallic matrix composite materials with ceramic reinforcement that can be potentially applicable as the substitute for cemented carbide. In our previous work, the route for the synthesis of nickel aluminide NiAl reinforced by Al_2O_3 particles (**Figure 5a**) or short fibres [13] and TiAl-Ti_5Si_3 in situ composite [11] was developed.

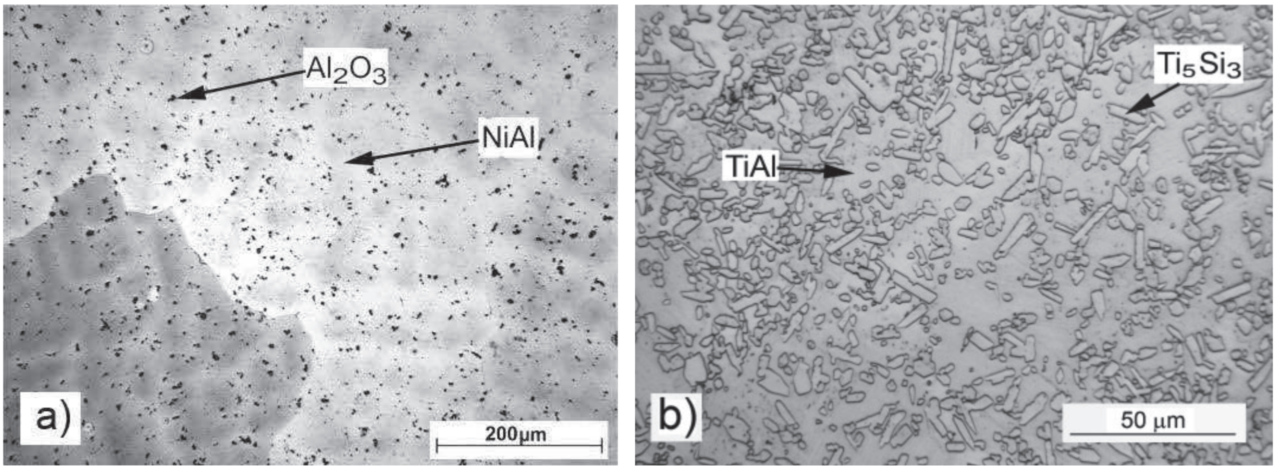

Figure 5 Microstructure of NiAl-Al_2O_3 composite [13] (a) and TiAl-Ti_5Si_3 in situ composite [11] (b) prepared by reactive sintering

Abrasive wear rate of selected materials based on intermetallics are presented in **Figure 6** in comparison with highly wear resistant tool steel AISI D2. Results show that single-phase intermetallics do not exhibit high wear resistance. On the other hand, the intermetallic-based composite materials achieve comparable (NiAl-Al_2O_3) or even much better wear resistance (TiAl-Ti_5Si_3) than highly wear resistant tool steel. The great advantage is that these materials achieve the wear rate in the same range as tool steels without the need of heat treatment.

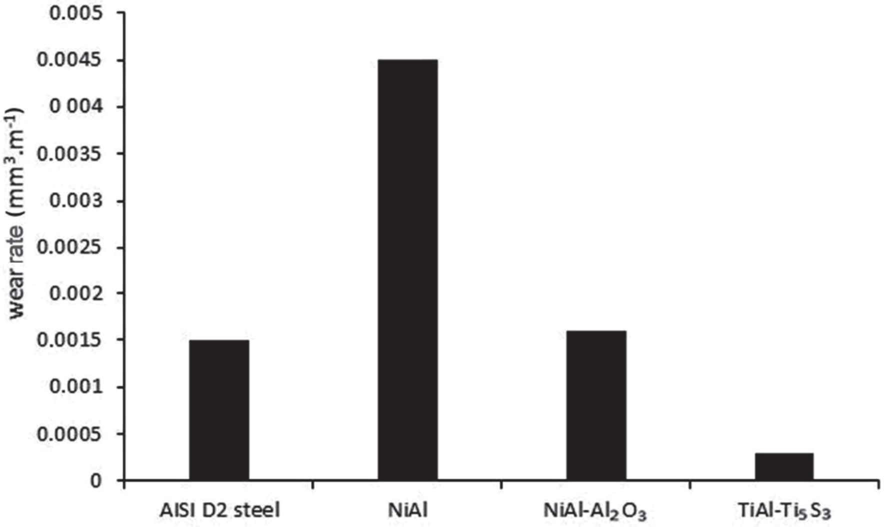

Figure 6 Abrasive wear rate of selected materials based on intermetallics (load 5.8 N, sliding distance 2500 m, grinding paper P1200)

5. CONCLUSION

This paper presents non-conventional methods in powder metallurgy processing of selected alloys, intermetallics and composites. Combination of mechanical alloying and suitable compaction technique (Spark Plasma Sintering) and reactive sintering of compressed powders seem to be the future of the production of high-grade materials. For selected applications, mainly in production of special materials based on intermetallics, reactive sintering is an interesting alternative processing route.

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