NON-CONVENTIONAL PROCESSING ROUTES AND APPLICATIONS OF INTERMETALLICS

NIEKONWENCJONALNE SPOSOBY PRZETWARZANIA I ZASTOSOWANIA MATERIAŁÓW NA OSNOWIE FAZ INTERMETALICZNYCH

Pavel NOVÁK[1]

Abstract: Intermetallics are materials offering wide variety of interesting properties, such as high hardness, high chemical resistance, shape memory or hydrogen storage ability. However, the synthesis and processing of intermetallic compounds by common metallurgical techniques is often very problematic. In this paper, the modern techniques involving non-conventional processes of powder metallurgy, reactive sintering and mechanical alloying, are presented. In the field of application, novel directions are linked – the use of intermetallic-based materials as surgical implants or tool materials.

Keywords: intermetallics, intermetallics-based composite materials, reactive sintering, mechanical alloying, applications of intermetallics, implant materials

Streszczenie: Materiały na osnowie faz intermetalicznych oferują szeroką gamę interesujących właściwości, takich jak wysoka twardość, wysoka odporność chemiczna, pamięć kształtu i zdolność do przechowywania wodoru. Jednakże synteza i wytwarzanie związków międzymetalicznych zwykłymi technikami metalurgicznymi jest często bardzo problematyczna. W niniejszej pracy zaprezentowano nowoczesne techniki obejmujące niekonwencjonalne procesy metalurgii proszków, spiekania reaktywnego i mechanicznego stopowania Wskazano nowe zastosowania materiałów na osnowie faz intermetalicznych, takie jak implanty chirurgiczne czy materiały narzędziowe.

Słowa kluczowe: materiały na osnowie faz intermetalicznych, spiekanie reaktywne, stopowanie mechaniczne, zastosowanie materiałów na osnowie faz intermetalicznych, materiały na implanty

---

[1] Institute of Chemical Technology, Prague, Department of Metals and Corrosion Engineering, Technicka 5, 166 28 Prague 6, Czech Republic, e-mail: panovak@vscht.cz

1. INTRODUCTION

Metallic materials are used in structural applications for their typical properties, such as good strength and ductility at common temperatures, formability, ductility, electric and thermal conductivity etc. In addition to these typical applications, metallic materials are also designed to be applied under the conditions near their limits, such as at high temperatures, in strongly aggressive corrosion environment or under the conditions of extreme abrasive or adhesive wear. For these conditions, intermetallics can be possible candidates, combining the properties of metals and ceramics. Intermetallics are usually characterized by high melting points, good corrosion resistance in electrolytes as well as at high temperatures or by special material-specific properties (shape memory, magnetic properties etc.). However, the larger utilization of intermetallics is strongly limited by low room-temperature ductility and also by problematic production and processing.

2. PRODUCTION OF INTERMETALLICS

Such as for other metallic materials, melting metallurgy is a dominant production method of intermetallics. Melting and casting is applicable technology for many intermetallics, but connected with serious problems. These complications are high melting points (e.g. titanium aluminide melts at 2130°C [1]), poor casting properties and also high reactivity of the melts at high temperatures (mainly in the case of the processing of titanium-based intermetallics [2]). All of those obstacles can be overcome by the modification of the processing route, such as the use of ultrasound during casting [3], hot isostatic pressing of the castings to heal the voids and cracks in castings [4] or the application of alternative less reactive materials for crucibles and molds (e.g. ZrO_2, Y_2O_3) [2]. However, these solutions increase the production cost and are not applicable generally. Forming processes are almost unapplicable for most of the intermetallics due to low plasticity even at elevated temperatures, except for e.g. NiTi shape memory phase.

These facts imply that powder metallurgy can be very promising alternative route for the production and processing of intermetallics. Among powder metallurgy techniques, two kinds of non-conventional processes play an important role worldwide. First one is mechanical alloying, which allows for the production of nanocrystalline intermetallics. Mechanical alloying is a solid-state powder processing method, involving repeated welding, fracturing and re-welding of powder particles [5] 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,
- formation of amorphous powders,
- alloying even by insoluble elements,
- low-temperature initiation of solid state reactions.

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 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 [6].

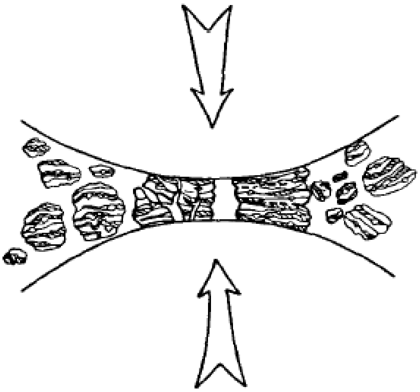

Figure 1. Schematic description of the mechanical alloying process [5]

Second possible method is a group of Self-propagating High-temperature Synthesis (SHS) processes. 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 (Fig. 2). After that, heat produced by the reactions sustains and propagates the reaction towards the body of the reactants [7]. In the case of heating of the sample, the process is usually called reactive sintering [7].

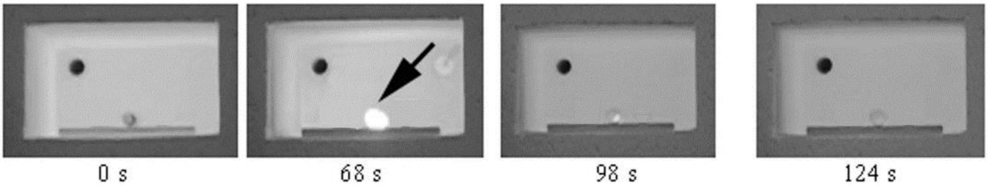

Figure 2. SHS progress in TiAl15Si15 powder mixture [8]

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 [7]. 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 [9].

3. APPLICATIONS OF INTERMETALLICS

One of the most typical applications of intermetallics is the high-temperature use. In our department, continuous research of high-temperature materials based on iron aluminide (FeAl) and titanium aluminide (TiAl) has been carried out since 2006. During this research, the in-situ composite TiAl-Ti_5Si_3 (Fig. 3) and its production route by reactive sintering were developed. During testing of this material it has been found that in addition to excellent high-temperature oxidation resistance (Fig. 4) this material exhibits also excellent abrasive wear resistance. Our preliminary results of mechanical testing and tribological tests show that this material can be potentially applied as a tool material.

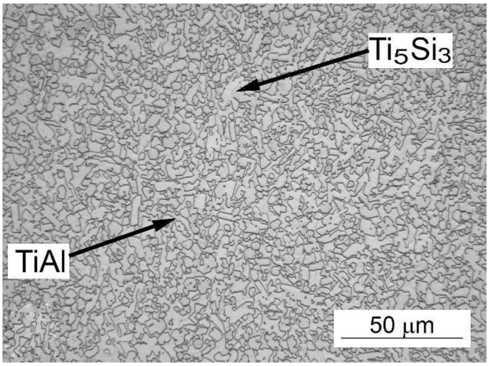

Figure 3. Microstructure of TiAl15Si15 alloy prepared by reactive sintering at 900°C for 15 min

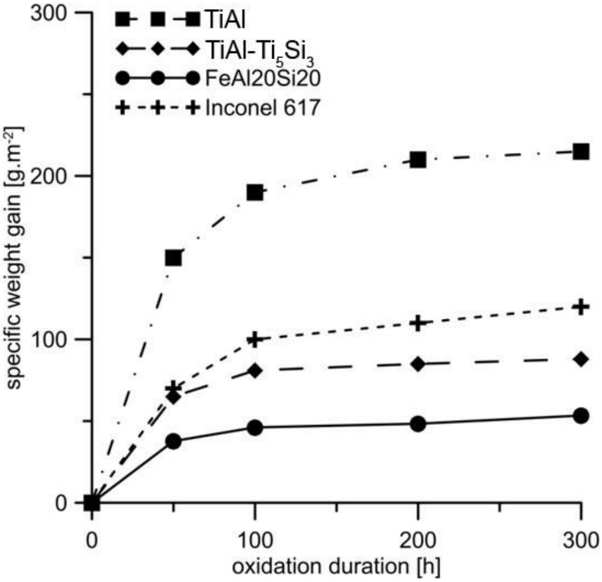

Figure 4. Weight gain during oxidation vs. oxidation duration at 900°C in air

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 [10], the route for the synthesis of nickel aluminide NiAl reinforced by Al_2O_3 particles (Fig. 5a) or short fibres (Fig. 5b).

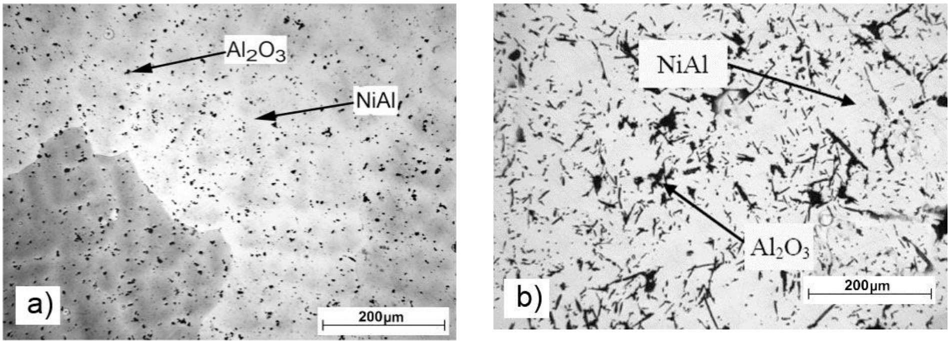

Figure 5. Microstructure of TiAl15Si15 alloy prepared by reactive sintering at 900°C for 15 min

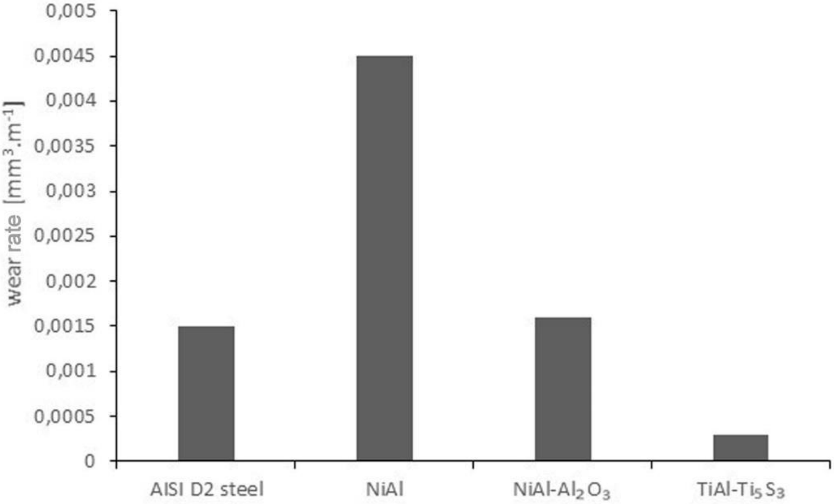

Figure 6. Abrasive wear rate of selected materials based on intermetallics
(load 5.8 N, sliding distance 2500 m, grinding paper P1200)

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 big advantage is that these materials achieve the wear rate in the same range as tool steels without the need of heat treatment.

The next non-conventional application of intermetallics is in the medicine. The branch of surgical and dental implants is usually a domain of conventional materials as stainless steels, titanium- or cobalt-based alloys. The exception is a NiTi shape memory alloy applicable e.g. for stents or braces. When this material is prepared by SHS, high porosity is usually achieved. This phenomenon is practically applied in the production of porous scaffolds made of NiTi phase [9]. It is considered or already applied in special medical applications, e.g. bone replacement. However, NiTi phase is not very biocompatible due to high amount of allergenic nickel. In our department we developed novel material containing titanium and silicon [11]. In this material, high porosity can be achieved during reactive sintering (Figure 7) under specific conditions without any additive. The pores form by Kirkendall effect and lattice distortion connected with the formation of silicides in the alloy. This material, covered by suitable bioactive surface layer, can be applied as a bone replacement, having porosity, mechanical properties and bioactivity comparable with human bone.

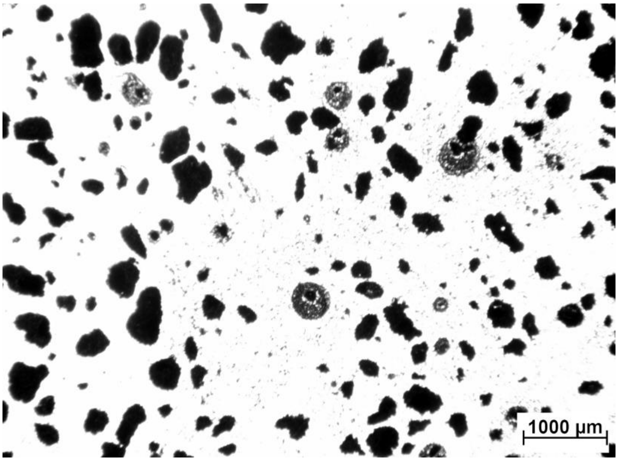

Figure 7. Structure of new titanium and silicon containing intermetallics-based biomaterial

CONCLUSIONS

This paper presents non-conventional methods for the synthesis of intermetallic compounds. These processes are based on modern powder metallurgical methods. 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 intermetallics and intermetallics-based composite materials.
Among the applications of intermetallics, the utilization as tool materials and new biomaterials for surgical applications can exceed the current application range in the near future.

ACKNOWLEDGEMENT

In this paper, the results of the project No. P108/12/G043 of Czech Science Foundation are presented.

LITERATURE

[1] MASSALSKI T.B., *Binary Alloy Phase Diagrams*, Materials Park, ASM, 1990.

[2] SADRNEZHAAD S.K., RAZ S.B., *Interaction between Refractory Crucible Materials and the Melted NiTi Shape-Memory Alloy*, In: Metallurgical and Materials Transactions B, 36, 2005, 395-403.

[3] ŠÍMA V., KRATOCHVÍL P., KOZELSKÝ P., SCHINDLER I., HÁNA P., *FeAl-based alloys cast in an ultrasound field*, In: International Journal of Materials Research, 100, 2009, 382-385.

[4] LAPIN J., HECHT U., *Effect of processing parameters on microstructure and mechanical properties of cast TiAl based alloys*, In: Metal 2008 conference proceedings, 2008, CD.

[5] FROES F.H., SURYANARAYAN C., RUSSELL K., LI C.-G., *Synthesis of intermetallics by mechanical alloying*, In: Materials Science and Engineering A192/193, 1995, 612-623.

[6] NOVÁK P., KUBATÍK T., VYSTRČIL J., HENDRYCH R., KŘÍŽ J., MLYNÁR J., VOJTĚCH D., *Powder metallurgy preparation of AleCueFe quasicrystals using mechanical alloying and Spark Plasma Sintering*, In: Intermetallics, 52, 2014, 131-137.

[7] NOVÁK P., MICHALCOVÁ A., ŠERÁK J., VOJTĚCH D., FABIÁN T., RANDÁKOVÁ S., PRŮŠA F., KNOTEK V., NOVÁK M., *Preparation of Ti–Al–Si alloys by reactive sintering*, In: Journal of Alloys and Compounds, 470, 2009, 123-126.

[8] NOVÁK P., POPELA T., KUBÁSEK J., ŠERÁK J., VOJTĚCH D., MICHALCOVÁ A., *Effect of reactive sintering conditions on microstructure of in-situ titanium aluminide-silicide composites*, In: Powder Metallurgy, 54, 2011, 50-55.

[9] KAYA M., ORHAN N., TOSUN G., *The effect of the combustion channels on the compressive strength of porous NiTi shape memory alloy fabricated by SHS as implant material*, In: Current Opinion in Solid State and Materials Science, 14, 2010, 21-25.

[10] NOVÁK P., ŠOTKA D., NOVÁK M., MICHALCOVÁ A., ŠERÁK J., VOJTĚCH D., *Production of NiAl–matrix composites by reactive sintering*, In: Powder Metallurgy, 54, 2011, 308-313.

[11] NOVAK P., *Titanium alloy for the manufacture of porous medical implants*, UV 26361, 2014.