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## PLASTIC CONSOLIDATION OF METALLIC POWDERS

### PLASTYCZNA KONSOLIDACJA PROSZKÓW METALICZNYCH

One of very well known methods applicable to conversion of dispersed materials to bulk state is traditional powder metallurgy process using densification and sintering. This paper will deal with consolidation process based on different idea to creation of strong cohesive bound between particles of dispersed materials. The main reason for consolidation, here, is large enough plastic deformation of powder particles produced in specific load and deformation state and it does not need intensive diffusion mass exchange between particles. Inversion of a decohesion process or creation of conditions for occurrence of internal bonding similar or identical to bounds taking place in bulk material needs to transform a material surface to state similar to that created just after surface origin, so to the state *instatu nascendi* and to bring such surfaces of particles to distance sufficiently small to enable conversion of strong interaction of short distance to permanent internal bonding. The most suitable process for this purpose is an extrusion at increased temperature. Conversion at such conditions can be named as plastic consolidation process, which does not need of activity of diffusion processes characteristic for sintering in conventional powder metallurgy. The process of plastic consolidation can be applied to synthesis of new material, production of composites and to recycling of fine forms of metals. The examples of such application have been presented.

*Keywords:* metal powder, metal recycling, composites, plastic deformation, powder consolidation, mechanical properties, aluminium alloys, magnesium alloys

Dobrze znaną metodą konwersji materiałów rozdrobnionych w materiały lite jest tradycyjna metalurgia proszków wykorzystująca operacje prasowania i spiekania. Niniejsza praca poświęcona jest procesowi konsolidacji proszków opartemu na odmiennej idei tworzenia silnych wiązań kohezyjnych pomiędzy cząstkami materiału rozdrobnionego. Podstawowym warunkiem, rozpatrywanego tu procesu, jest dostatecznie duże odkształcenie plastyczne cząstek rozdrobnionych przeprowadzone w warunkach specyficznego stanu odkształcenia i naprężenia, a sam proces tworzenia wiązań kohezyjnych nie wymaga dyfuzyjnej wymiany masy pomiędzy cząstkami. Odwrócenie procesu dekohezji lub tworzenie warunków dla wystąpienia wewnętrznych wiązań podobnych lub identycznych z wiązaniami występującymi w materiale litym wymaga przekształcenia powierzchni cząstek do stanu podobnego do powierzchni tuż po jej utworzeniu, czyli do stanu *instatu nascendi* i zbliżenia takich powierzchni na odległość wystarczającą dla przekształcenia silnych oddziaływań bliskiego zasięgu w trwałe wiązanie wewnętrzne. Najbardziej korzystnym procesem do takiego celu jest wyciskanie w podwyższonych temperaturach. Konwersję w takich warunkach można nazwać konsolidacją plastyczną, która nie wymaga uruchomienia procesów dyfuzyjnych charakterystycznych dla spiekania w konwencjonalnych procesach metalurgii proszków. Proces plastycznej konsolidacji może być stosowany do produkcji nowych materiałów, wytwarzania kompozytów oraz do recyklingu drobnych odpadów metalowych. Przykłady takich zastosowań są przedstawione w prezentowanej pracy.

### 1. Introduction

Necessity of the diminution energy and material consumption, as condition of sustainable growth and rational use of the non-renewable natural resources is the challenges of the present economy. These aims, in majority of cases, are possible to reach by replacement of the traditional materials by the new ones that have enlarged specific strength or better functional properties.

The achieved here advantages have the two-fold kind of source. Firstly, raising the durability and resistance on aggressive environmental factors of the new materials with simultaneous maximization of grade of recycling, reduce demand on primary materials, production of which is usually the most energy-consuming part of the production and exploitation processes. Secondly, such materials increase the energetic efficiency of constructions by lowering their weight as well as by rise of

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load-carrying capacity. This has a special meaning for vehicles, the movable parts of construction, heavy laden electrically and mechanically construction elements as well as the electric transmission lines [1].

Fragmentation of crystallites to nano/submicron scale is the natural reserve of the strength increase without degradation of plasticity necessary for constructional application (fracture toughness) as well as the corrosion resistance [2]. Alloy additions in such materials can further enlarge mechanical properties, their stability in raised temperatures, corrosion resistance and abrasive properties. There are described dozen or so methods of production of metallic materials with refined grain structure by severe plastic deformation (SPD). The serious technical problem of these methods is limited dimensions of products as well as susceptibility to grain size instability manifesting itself by spontaneous process of recrystallisation or growth of crystallites. They are, however, method that solves that problem by elastic assembly of several technological processes [3]. The example of this is production of hyper eutectic silumins with hybrid structure stabilised by considerable quantity of the nanometric (~30nm) particles of intermetallic phases, in which the fragmentation is a results of rapid crystallization. Such effect is attainable at atomisation process of liquid metals used to production of metal powders or flakes. The consolidation of such powders permits to get the bulk material [4÷7]. Use of this method to rapidly solidified powders of aluminium, alloys of aluminium, and electrolytic powders of copper or silver creates the chances for producing the large products with nano/submicron structure and high mechanical properties, good plasticity as well as high electric conductivity. The critical step of this method is conversion of material with highly dispersed state (powders or other fine products of rapid solidification) to the bulk one [8÷10].

One of very well known methods applicable to this purpose is traditional powder metallurgy process using densification and sintering. An elementary process involved to conversion of powder particles to bulk state for this method is diffusion, which by local mass transfer leads to creation of strong cohesive bounds. Unfortunately, such process leads to materials with substantial porosity which reduce the mechanical as well plastic properties of product and due to elongated time of high temperature treatment, destabilise fine grain structure. In addition, in materials with strong chemical affinity to oxygen (aluminium, magnesium etc.) the oxides layers on the powder particles preclude creation of strong, cohesive bounds between particles in material due to impossible reduction of oxides in traditional atmosphere of sintering process. In results the properties of product of

such methods of consolidation are far from expectation [10].

This paper will deal with consolidation process based on different idea to creation of strong cohesive bound between particles of dispersed materials. The main reason for consolidation, here, is large enough plastic deformation of powder particles produced in specific load and deformation state and it does not need intensive diffusion mass exchange between particles. Therefore process can be named as plastic consolidation [9, 11].

## 2. Dispersed state of solids

Properties of constructional materials can be controlled by change of grain structure. These changes can be induced by an application of proper mechanical and thermal treatment or by a modification of chemical composition of materials. In this last case the interrelation of nucleation and growth of crystallites processes at crystallization from liquid state by influence on intensity of nucleation process and/or slowing down of grain growth is utilized. Theoretically, similar effect would be attained without inoculants in form of additional alloying element by induction sufficiently high overcooling at crystallization. This can be put into effect at very high cooling rate, which can not be attained for massive object due to physical limitation of a heat transfer, determined by heat conductivity and length of heat transfer path. Desirable effect can be achieved in the objects with very strong limited dimensions only, which can not be applied to constructional purpose [12÷13].

A solution of overcooling problem is atomization of liquid material and then its crystallization in dispersed form. Application of this method enable production of material with highly refined grains in small particles separated from other ones by free phase surface. It can be, thus, produced material with desirable structure and properties but in dispersed form. This form can be defined as particles set with small dimensions in which interaction between the particles are absent or the interaction are weak enough to be destructed by gravity forces acting on the particles. Characteristic feature of such particles set is highly developed free surface in comparing to particles volume in the set. Since the free surface poses increased energy in comparison to volume energy, the entire energy of the set has the increased energy too in relation to energy of this same volume of material in a bulk state [14]. Differences in different parameters between dispersed form with particles size of 40  $\mu\text{m}$  and the bulk one for 1 kg of aluminium can be observed on the basis of data gathered in table 1.

Small size of metal particles in dispersed state creates the many technological opportunities for forming their interior structure which are inaccessible in bulk state. As has been mentioned above, possibility of rapid changes of temperature could be a base for overcooling modification of grain size or creation of amorphous structure. It enable severe plastic deformation of particles in high energy milling process and obtain in this way mechanically alloyed materials with structure and properties inaccessible in traditional processes of new material synthesis. They create possibility for composing of multiphase mixtures for production of composites.

TABLE 1

Comparison of some parameters for bulk and dispersed forms of aluminium

| Parameter                      | Bulk form | Dispersed form          |
|--------------------------------|-----------|-------------------------|
| Material mass [kg]             | 1         | 1                       |
| Particle dimension [mm]        | 89.10     | 0.04                    |
| Number of particles            | 1         | $1.1052 \times 10^{10}$ |
| Free surface [m <sup>2</sup> ] | 0.0249    | 55.5534                 |
| Surface energy [mJ]            | 37.41     | 83330.12                |

Dispersed state of material could be attained by induction of decohesion effect in condensed matter in both liquid and solid state. Phase transformation in small particles does not influence their dispersion. Therefore, attaining of dispersed state is possible in both atomization from liquid state and by generation of intensive cracking process in solids. One of typical example for this last process is machining, where mechanical stock removal based on fracture effect in micro volume leads to creation of waste in dispersed form. Effective and economically profitable recycling of such wastes is one of the challenges of a temporary technology [15, 16].

Another way for attaining of dispersed state of materials is utilizing of electrolytic processes at proper conditions or reduction of oxides in solids state, where getting of product in bulk or liquid state is impossible or technically not advisable. The particles in dispersed state can have different shape from spherical to highly developed dendrite and porous form [17]. Shape of particles strongly influences the entirely free surface of particles set, their energetic state and technologic properties. Presented in the table 1 parameters are related to the spherical particles, where the surface and surface energy is smallest. The each shape change, which move out the shape from spherical form, as well as decreasing of particle dimension leads to increasing of energy of entire system.

All processes of dispersed state production need a work done by external forces. A part of this work is retaining in material in form of surface free energy. In-

creasing of entire energy of dispersed state in relation to the bulk one suggests the process of particles integration to be spontaneous at conditions created for recohension process. One of result of strong developing of surface is the intensification of surface effects which leads to creation of adsorption layers and surface chemical compounds on individual particles. These layers make the interaction between particles weaker and they fix the dispersed state by making the recohension difficult. Their elimination or limitation of their presence on particle free surface is a one of necessary condition for conversion of dispersion state to the bulk one.

### 3. Necessary conditions for plastic consolidation

A process of transformation of dispersed state of crystallized water in snow form to solid ice is observed in the nature. Effect takes place at a high unit pressure and slow plastic flow induced by gravity forces. In result, mountain glaciers flow from top parts of mountains to the valleys. This process illustrates possibility of conversion of dispersed form (snow) to the bulk one (ice), that is the consolidation process.

Inversion of a decohesion process or creation of conditions for occurrence of internal bonding similar or identical to bounds taking place in bulk material needs to transform a material surface, at least locally, to state similar or identical to that created just after surface origin, so to the state *instatu nascendi* and to bring such surfaces of particles to distance sufficiently small to enable conversion of strong interaction of short distance to permanent internal bonding. Therefore, it could be formulate postulates which are necessary to be fulfilled for realization of such process. These postulates are:

- The adsorbed and the chemical compound layers deposited on surfaces of particles, which are objects of conversion, must be removed or a part of surface occupied by this layer must be strongly limited.
- The particles surfaces must be strictly fitted each to other.
- The close up of particles surfaces for atomic distance, so for the distance of short distance interaction must be realized.

All these postulates should to be fulfilled concurrently in the time period and conditions which preclude covering of the particles by new layers. Hence, they should be fulfilled in one operation of this same process.

The first postulate could be fulfilled, at least partly, by severe plastic deformation at conditions providing desorption process. It is possible increased temperature and/or at decreasing of pressure over the particles surface. Plastic deformation always leads to change of surface area to volume ratio of deformed object, therefore,

taking into account the rule of constant volume the deformation always leads to change in surface area. If the changes of shape induced by deformation leads to developing of surface area then the new created area has the features of *instatu nascendi* surface and fulfilled the reasons of the first postulate [11]. Scheme of the change of an object of spherical to ellipsoid shape is illustrated on Fig. 1.



Fig. 1. Scheme of the change of an object of spherical to ellipsoid shape

Assuming the constant volume of object and defining a coefficient of area developing  $K$ , as a ratio of a surface area after deformation to a surface area before deformation of object and assuming the elongation  $\lambda = A_1/A_0$  (where the  $A_0$  is area of cross section before deformation and the  $A_1$  is the area of cross section after deformation perpendicular to deformation direction) it could be show, that for deformation of a spherical object to a ellipsoid of revolution the coefficient  $K \approx (\lambda/2)^{1/2}$ . For deformation of a spherical object to a flattened spheroid  $K \approx \lambda/3$ , and for deformation of a flattened spheroid to an elongated flattened spheroid  $K \approx \lambda$ . Assuming for extrusion process  $\lambda = 20$ , which is a low vale in real process, developing of surface area for such deformation process are of  $K \approx 3,16$  for deformation of a spherical object to a ellipsoid of revolution and to  $K \approx 20$  for deformation of a flattened spheroid to an elongated flattened spheroid. It means that over the 68% of surface area for this first case and 95% of surface area for this last case is the newly created surface [11]. The surface created in deformation process are *instatu nascendi* surface and fulfil the reasons for first postulate for creation of cohesive bound, particularly when the deformation is fast enough at conditions preclude creation of adsorption or chemical compound layers. It is worth to note, that the increase of *instatu nascendi* surface are greater for deformation of particles differ from spherical shape, which point to possibility of convenience for processes based on developing of new surface at deformation of irregular shape of particles. However, it should be tacking into account homogeneity of surface developing. This last feature deteriorates for deformation of non equiaxial object. From this point of view an initial shape of particles is not neutral for quality of developed surface and it can be the parameter which should to be optimized for processes basing on creation of *instatu nascendi* surface.

If a collective deformation of particles is performed, that means the particles set is deformed in the way where forces are relaying by deforming particles to other one

and the particles are simultaneously deformation objects and forming tools. Then the flow of particles leads to fill voids between particles and to fit surfaces of particles each to other similar to deformation in die forming processes. Hence, it is fulfilled the second postulate at such reasons. Further assuming deformation at the very high hydrostatic pressures on the level much more higher then flow stress it is possible to get the reasons fulfilled the third postulate on the closing up of particles to distance enabling activation of short range interaction, which are necessary to creation of cohesive bound between *instatu nascendi* surface.

The above consideration has been performed at assumption, that the particles have ability to plastic deformation, and in consequences are able to create a new surface. So, the such material can be converted from dispersed state to the bulk one in plastic deformation operations providing that the mentioned before remain postulates are fulfilled. Such process can be, therefore, named as plastic consolidation process, which does not need of activity of diffusion processes characteristic for sintering in conventional powder metallurgy. It seems to be, that the most suitable process of metal working for this case is the process of extrusion in increased temperature, although other processes in increased temperature which are able to provide high hydrostatic state of stress and high enough deformation can fulfil the mentioned postulates too. Results of research of such process show, that for materials based on aluminium extrusion process performed above 250C and at the elongation ratio  $\lambda > 6 \div 9$  give the satisfy results in form of fully consolidate material with small amount of internal imperfections, which could be eliminated by a consecutive plastic working [9, 10, 11, 18]. Research results indicate too, that such process can be performed successfully for mixtures of powders containing the plastically non deformable particles, providing sufficiently high portion of plastically deformable powders, which are able to fulfil early formulated postulates [11].

Increasing of process temperature is usually sufficient condition for carrying out of desorption process and prevention of *instatu nascendi* surface against a renewing of adsorption layer. It decreases the stress necessary to plastic flow of particles. Hence, increased temperature play a different role comparing the sintering process where temperature are necessary to activation of diffusion process, which additionally needs long enough time for successful consolidation. In the case of plastic consolidation temperature is much lower and the time of exposition of material to increased temperature is meaningful shorter, therefore, the plastic consolidation process creates the reason for limitation of processes of destabilizing of dispersed material structure. It could be

expected, the consolidate material structure will inherit in substantial degree the structure of dispersed material. Choice of proper temperature of process is, therefore, a next parameter, which should to be optimized due to technological needs and properties of produced material.

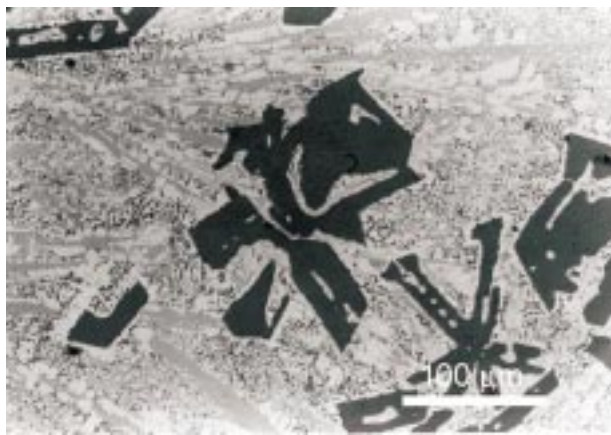
#### 4. Examples of plastic consolidation of metallic materials

Described above process of plastic consolidation can be applied in three area of materials technology. The first area of application are technologies of new materials production basing on rapid solidification process, where material in dispersed form of powders or flakes is obtained by atomization from liquid state and then are plastically consolidated. By this method there are possibilities to get the engineering materials, which are not accessible by conventional metallurgical ways [4, 6, and 7]. In addition, conventional materials produced by such technologies pose properties which are not attainable in traditional processes [19]. The second area of application is production of composite materials with small or moderate content of reinforcing phases by plastic consolidation of powder mixtures containing particles or short fibres of hard materials [20]. In this case there are possible to get homogenous distribution of reinforcing elements and there are opportunity to omit the problem of danger compound production on interface between matrix and reinforcement. In this case, however, particular attention should by pay for conditions which allow to get good integration of reinforcement with matrix due to small plasticity or brittleness (usually) of reinforcement. The third application area for plastic consolidation is recycling processes of wastes created in machining; comminute scraps or fine form of secondary materials [16, 21]. Such wastes are usually included to materials, which are hard to rework in conventional metallurgical processes. Highly developed surface area of such wastes leads to high loss of metal at melting due to intensive oxidation in high temperatures. It is particularly important for materials with high chemical affinity to oxygen, where even application of special coverage and protection or reduction atmospheres do not protect sufficiently against creation of heavy oxide layers. These layers are basic sources of irreversible losses of recycled materials. Application of plastic consolidation for recycling of fine form of wastes allows to substantially increasing efficiency of process and can be treated as an effective alternative for closing of material circulation in economy at elimination of danger wastes for environmental, which are created at traditional scrap processing by melting [16].

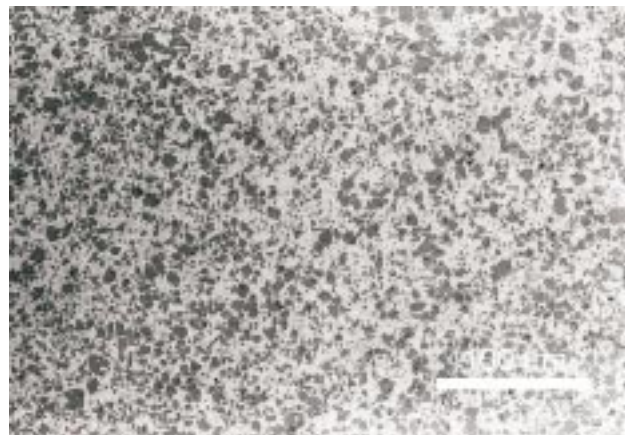
An example of unconventional engineering materials produced by rapid solidification and plastic consolidation are hypereutectic aluminium silicon alloys (silumins) with substantial addition of nickel or nickel and iron. Usable forms of alloys containing 24% of silicon and 6%÷8% of nickel can not be obtained in conventional process of casting and plastic working due to unfavourable structure of primary silicon and intermetallic phase's crystallites, which lead to intrinsic cracks and decay of plastic deformation ability. Application of rapid solidification changes the structure radically. Dispersed forms produced by this technique have a hybrid nanometre-ultra fine grained structure with equiaxial grains of few tens nanometres up to few micrometers diameters and very good mechanical and functional properties [4, 5, 22].

Structure of AlSi24Ni8 alloy as cast and plastically consolidated after rapid solidification to particles size of 200  $\mu\text{m}$  and 50 $\mu\text{m}$  are illustrated on Fig. 2. Processes of rapid solidification and plastic consolidation by extrusion, lead to overall redevelopment of material structure. Present in the as cast state long needles of primary silicon placed in plate like eutectic of aluminium and silicon are completed by very large inclusion of intermetallic phases with strongly developed surface (Chinese letter). This structure has a very high internal stresses due to large differences of thermal expansion coefficient between phases components, which leads to spontaneous intrinsic cracks. Atomisation in liquid state and rapid crystallization produces the high refining of structure, which depends on the cooling rate. This last parameter is depending on heat transfer from liquid drop, so it depends on the drop size. Therefore, the size of basic elements of structure solidified drops strongly depends on particle size of produced powder. Fractionation of produced powder allows getting material with different parameters of initial structure, which after plastic consolidation is "inherited" by the product. Refining of structure of considered alloy is large enough to observe the biggest element of it only by using the light microscope techniques. These elements are the equiaxial primary grains of silicon with diameter of few micrometers. The remaining elements of structure are hardly visible in such observation due to too small resolution of this technique [23].

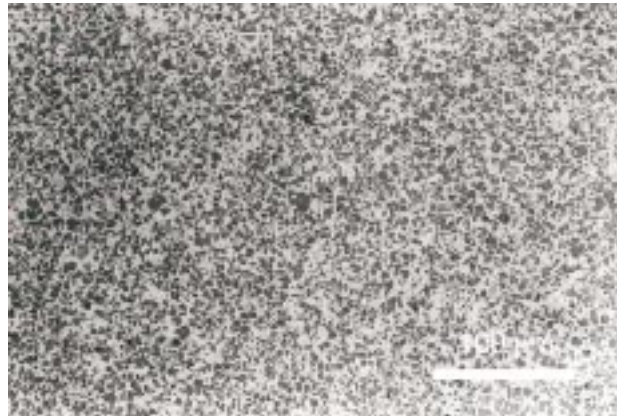
The structure could be observed by using of electron microscopy. The examples of such structures are shown on the Fig. 3. Very rapid cooling rate at crystallization of the order of  $10^4$  K/s leads to creation of granular aluminium silicon eutectic with grain size of range of 300 nm to 700 nm. The grains boundaries of this eutectic are decorated by very fine precipitations of intermetallic NiAl phases with grain size of ranges from few tens to



a)

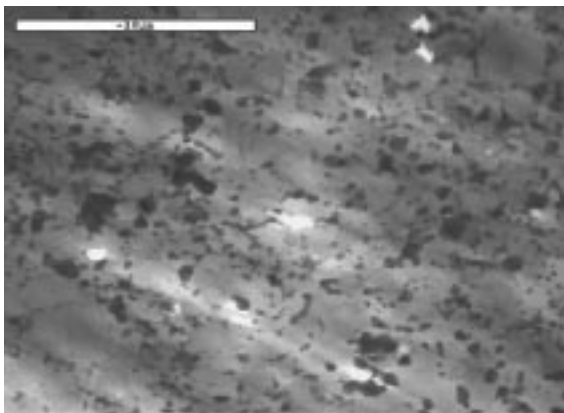


b)

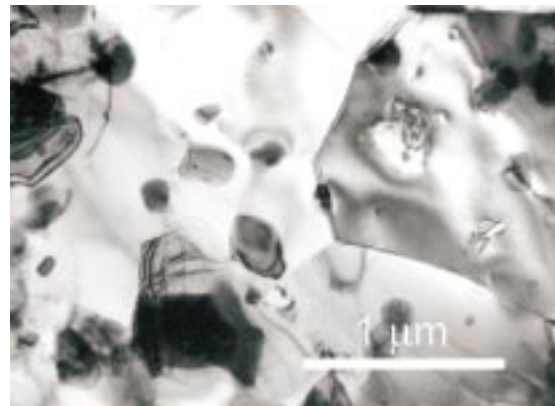


c)

Fig. 2. Structure of AlSi<sub>24</sub>Ni<sub>8</sub> alloy; as cast (a), after plastic consolidation of rapidly solidified powder with particles size 200 μm (b), after plastic consolidation of rapidly solidified powder with particles size 50 μm (c)



a)



b)

Fig. 3. Structure of AlSi<sub>24</sub>Ni<sub>8</sub> alloy observed by electron microscopy using STEM technique (a) and TEM technique (b)

two hundreds nanometres. This last phases stabilize very effective the structure by retarding of their growth even at the high temperature deformation process [22, 23].

Described fine grained structure and its thermal stability produce ability to substantial plastic deformation,

particularly in increased temperature. This feature make possible to form plastically products by die forging or any other plastic working process. An additional consequence of such fine grained structure is very high mechanical properties of the material. The yield stresses in

compression tests for considered material are presented in Table 2.

TABLE 2  
Yield stresses of AlSi24Ni8 alloy after plastic consolidation and die forging

| Test temperature [C] | After consolidation [MPa] | Die forged piston [MPa] |      |
|----------------------|---------------------------|-------------------------|------|
|                      |                           | crone                   | wall |
| 20                   | 308                       | 524                     | 444  |
| 220                  | 265                       | 341                     | 311  |
| 340                  | 139                       | 159                     | 145  |

Increasing of mechanical properties after additional plastic working operation is a result of increased plastic deformation, which leads to advancement of plastic consolidation process, by further developing of primary particles surface. This improves a tenacity of material and eliminates the places where cohesive bondings created in primary consolidation process were not generated. Characteristic feature is relatively high differences

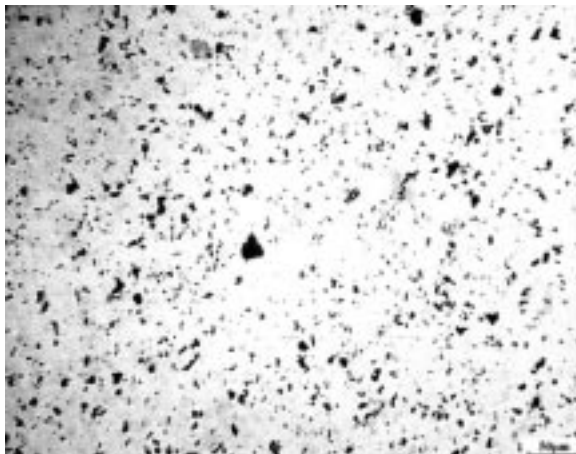
in mechanical properties between crone and side wall of forged piston with advantage for piston crone [23]. This is a consequence of different stress state in these two parts of product in forging operation. In the crone of piston the stress state is close to hydrostatic compression while in the side wall of piston tensile stresses can be induced by free surface and friction between a tool and material, so the conditions for improving of tenacity in the wall are worse comparing to crone.

Application of the rapid solidification and plastic consolidation for conventional aluminium alloys leads in result to materials with mechanical properties two-fold, for some cases three-fold, higher at retaining comparable plasticity in comparison to materials produced by traditional methods [19]. This is illustrated by examples presented in Table 3. The properties of materials produced by considered technology are comparable to properties of material after heat treatment but much more thermally stable and more resistive to corrosion and fatigue.

TABLE 3  
Mechanical properties of traditional alloys after rapid solidification and plastic consolidation. For comparison properties of this same material after extrusion in conventional process are inserted as "state O"

| Alloy | Consolidation parameters           | Y.S. MPa     |           | UTS. MPa     |           | A5, %        |           |
|-------|------------------------------------|--------------|-----------|--------------|-----------|--------------|-----------|
|       |                                    | Consolidated | State "O" | Consolidated | State "O" | Consolidated | State "O" |
| 5083  | $420^{\circ}\text{C}/\lambda = 45$ | 423          | 145       | 467          | 290       | 18           | 22        |
| 5056  | $420^{\circ}\text{C}/\lambda = 45$ | 295          | 152       | 383          | 290       | 20           | 35        |
| 442.0 | $420^{\circ}\text{C}/\lambda = 45$ | 494          | 145*      | 609          | 214*      | 2.2          | 2.5*      |
| 4047  | $420^{\circ}\text{C}/\lambda = 45$ | 154          | 70        | 221          | 145       | 22           | 22        |

\* as cast state.



a)



b)

Fig. 4. Structure of aluminium 5% graphite composite consolidated from elementary powders. Not etched cross section of extruded rod (a), and section along the rod axis (b)

Properties of aluminium matrix composites produced by plastic consolidation

| Materials                           | Y.S. MPa | U.T.S. MPa | HV | A5 % | Other properties  |
|-------------------------------------|----------|------------|----|------|---|
| Al+2%Al <sub>2</sub> O <sub>3</sub> | 145.7    | 156.5      | 50 | 13.3 | increased wear resistance                               |
| Al+2%Diamant                        | 151.6    | 158.2      | 48 | 11.6 | increased friction coefficient                          |
| Al+5%Graphite                       | 148.2    | 151.4      | 49 | 14.6 | decreased friction coefficient, increased machinability |
| Al+22%Si                            | 132.1    | 141.8      | 53 | 5.9  | decreased CTE, increased stiffness                      |

Another important area of application of plastic consolidation technology can be production of metal matrix composites reinforced by particles and short fibres. Application of this technique provides very good homogeneity of reinforcement in whole composite volume and creates possibility for controlling of matrix grain size, which influence essentially on mechanical properties of product. Composites produced by this route can pose modified functional properties, which are hardly attainable in conventional alloys [20]. In addition, at plastic consolidation, a creation of danger compound layers on interface between matrix and reinforcement is limited due to low temperature and short time of operation. Examples of aluminium graphite composite structure with features mentioned above are shown on Fig. 4.

Mechanical properties and some characteristic feature of such composites are presented in Table 4. In the case of application of reinforcement, which is not deformable plastically, an amount of reinforcement phase must be limited, however, properties of produced materials by this technology are higher than similar composites produced by casting methods. Very good results is attained at application of plastic consolidation for synthesis of metal – metal composites, where both matrix and reinforcement are plastically deformable and the low temperature and short time of process prevent against intensive diffusion and provide retaining of individual features of components in composite [20, 24].

Application of plastic consolidation as a method for recycling of dispersed metals waste seems to be one of the well economically grounded methods in this area. It is particularly advisable for materials, which have high chemical affinity to oxygen, as in case of aluminium and magnesium alloys. Such materials at processing by traditional cast methods undergo a heavily oxidation, which is the reason for strong diminishing of efficiency of metal recovery. In extreme cases metal losses can achieve 45% of metal weight [16]. In addition it is difficult to recover some times valuable alloy components, which are, as a rule, removed in refining processes and melting losses forming in such process are danger wastes for environment. Application of plastic consolidation as a

recycling method needs a careful management of wastes only. It needs to keep the sorting of wastes according to the alloys grade. After pre working, which consist in recovery of coolant and other surface active agents and after gas and moisture desorption the wastes can be plastically consolidated by hot extrusion or any other metal working process. Produced in this way bulk materials have the properties close to primary material used to machining. A further metal working and heat treatment are able to improve properties to the level require for the origin materials produced by conventional route.

Examples of application of the method for recycling of fine form of aluminium formed at production of aluminium foil, worked out of electric wiring and other fine form of aluminium are presented in Fig. 5 and Table 5. Properties of materials obtained by plastic consolidation of atomised powders and shots are substantially higher in comparison to similar material extruded from bulk ingot. It is a result of strong refining of the grain structure obtained at rapid solidification in atomization process. Influence of crystallization rate is demonstrated by material properties produced from powder with 150 µm particle size and shot with particle size of order of 1.5 mm. The size of particle influence on heat transfer rate at crystallization and it leads to different grain size in material after consolidation and according to Hall-Petch relation to different mechanical properties. A natural consequence of flow stress and strength increase in materials is lowering of elongation due to promotion of instability of flow at tensile tests, however, reduction of area at necking indicate the high plasticity and ability to further plastic working of considered materials.

Decreasing of elongation in tensile tests for some cases of consolidation can be a result of micro defects in form of local absence of cohesion on boundaries created by primary free surface of particles. Further plastic working application creates possibility to elimination of such defects and improving of mechanical and plastic properties in similar way as have been observed for material AlSi24Ni8 after die forging. Comparison of mechanical properties for materials plastically consolidated and similar materials produced by conventional way (Table 5) point to possibility to obtain by plastic consolidation



method materials with these same or better properties as materials produced by conventional route. Unquestionable advantage of plastic consolidation method for recycling is limitation of irreversible losses of metal and substantial diminishing of energy-consumption of process.

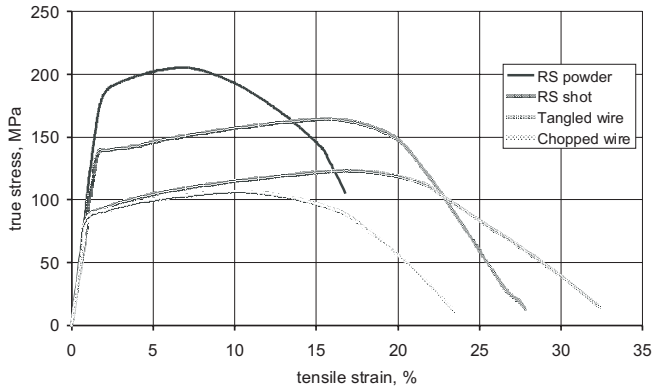


Fig. 5. Tensile curves of aluminium after plastic consolidation of dispersed form

TABLE 5

Mechanical properties of aluminium products after plastic consolidation by hot extrusion of different dispersed form and product obtained by extrusion of bulk ingot of his same material

| Material     | Y.S., MPa | U.T.S., MPa | HV   | A <sub>5</sub> % |
|--------------|-----------|-------------|------|------------------|
| RS powder    | 171.0     | 183.0       | 51.4 | 20.1             |
| RS shot      | 136.3     | 141.3       | 38.3 | 27.0             |
| Foil         | 94.5      | 131.9       | 35.3 | 31.6             |
| Chopped wire | 82.7      | 99.3        | 30.4 | 23.0             |
| Tangled wire | 83.3      | 96.1        | 29.7 | 34.1             |
| Bulk A1      | 86.2      | 101.1       | 30.1 | 31.6             |

TABLE 6

Mechanical properties of magnesium alloy AZ91D in as cast state, after extrusion by different methods and plastically consolidated from chips

| Material           | Y.S. [MPa] | U.T.S. [MPa] | A <sub>5</sub> % |
|--------------------|------------|--------------|------------------|
| Bulk extruded      | 244        | 342          | 12               |
| Bulk KOBO extruded | 205        | 293          | 9                |
| Chips extruded     | 243        | 346          | 8                |
| As cast            | 150        | 230          | 3                |

Another example of use the plastic consolidation for recycling of wastes produced at machining are magnesium alloys (Table 6). Extrusion of bulk as cast materials by both conventional as well as KOBO methods provides material with strongly increased mechanical and plastic

properties comparing to material in the as cast state. This is a result of rebuilding of course-grained dendritic structure of cast into homogeneous and highly refined grain structure after extrusion. Plastic consolidation of chips provides material with similar mechanical properties as extruded from bulk state and little smaller elongation but still higher as obtained for as cast state. The reason for lowering of elongation for material consolidated from chips is similar to that considered for aluminium and further plastic working create possibility for improving of this property.

Presented examples illustrate a range of application of the plastic consolidation in technology of materials, which are plastically deformable. A practical application of such technology can be based on very well known and controlled technical solutions applied in industrial scale. It leads to cost reduction at implementation of technology and make it competitive from cost, environmental protection as well as from quality of products point of view. An important feature of plastic consolidation process seems to be its flexibility in relation to production scale. Process can be applied with a good results in both small as well as great industrial scale depend on kind of produced material and plastic working method applied to consolidation.

## 5. Final remarks

Application of plastic consolidation as a way for conversion of dispersed state of material to bulk one is based on non-diffusion concept for creation of cohesive bound. View on such consolidation as an effect reverse to decohesion, it means the effect of which physical aspects are an object of many research projects, opens possibility to utility the knowledge gathered in this area for improving of the process. Its allow change radically principles of technology design for production of materials with controlled structure and properties. Utilization of advantages of rapid solidification for formation of ultra fine grained structure needs to avoid prolonged and high temperature processes, which in natural way leads to destabilizing of such structures. The plastic consolidation creates such possibility and enables production of constructional materials with unique properties basing on materials which are treated up to now as impossible to production due to technological limitation. It creates too, possibility for basing of some processes on effects absent in the industrial practice up to now. Possibility of excluding of high temperature operations at this kind of conversion makes additional serious simplification of technology and posses significant advantage in economical aspect of process. Therefore, this technology

seems to be important element in concept of sustainable growth.

#### Acknowledgements

The work was performed in the frame of statutory grant of Ministry of Science and Higher Education No 11.11.180.134.

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