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A NEW INDUSTRIAL-SCALE METHOD OF THE MANUFACTURING OF THE GRADIENT STRUCTURE MATERIALS AND ITS APPLICATION

NOWA TECHNOLOGIA UZYSKIWANIA MATERIAŁÓW O STRUKTURZE GRADIENTOWEJ NA SKALĘ PRZEMYSŁOWĄ I JEJ APLIKACJE

The article describes a novel manufacturing method of materials which exhibit variation in microstructure and thus functional properties along the direction perpendicular to the surface of material. The practical realization of the technological process is based on the combination of surface burnishing with friction heating resulted from the interaction of the tool tip with the material surface. This combination, by creation of specific conditions for plastic deformation, results in the formation of a material with the gradient microstructure which, in turn, contributes to the superior surface layer quality. The obtained results showed that the application of this method, in industrial practice, to porous materials may lead to the formation of the compact, void-free layers with the variable thickness on material surfaces and simultaneously keep geometrical dimensions of the final product with a required accuracy. The presented research pertains to the application of this method to the cast aluminum alloys used for casings of high-voltage switchgear and control gear which are filled with electroinsulating SF_6 gas. The commonly used alloy for this purpose is an aluminum alloy in EN AC-42100 temper (Si 6.5 - 7.5 wt%, Mg 0.25 - 0.45 wt%). The alloy is characterized by good casting and mechanical properties as well as heat treatment ability. However, the products obtained in the casting technology may contain structural discontinuities (porosity, shrinkage porosity). During machining operations, the presence of porosity in a material may be a cause of defectiveness due to high requirements imposed by the leak tightness of flange joints.

Keywords: gradient materials, FGM, aluminum alloys, porosity, plastic deformation

Praca dotyczy badań nad nową technologią uzyskiwania wyrobów o zmiennej strukturze i własnościach użytkowych na kierunku prostopadłym do powierzchni materiału. Praktyczna realizacja procesu technologicznego polega na połączeniu nagniatania powierzchniowego z nagrzewaniem tarciowym w celu wytworzenia warunków niezbędnych do odkształcenia plastycznego materiału. Zastosowane rozwiązanie umożliwia uzyskiwanie materiału o strukturze gradientowej. Zaprezentowana metoda ingerencji w materiał pozwala m.in. na otrzymanie wyrobów o podwyższonej jakości warstwy przypowierzchniowej. Uzyskane wyniki badań własności użytkowych wyrobów, cechujących się strukturą porowatą, wskazują na możliwość wytwarzania litych, pozbawionych nieciągłości warstw powierzchniowych o zmiennej grubości w warunkach przemysłowych, przy jednoczesnym zagwarantowaniu wymiarów geometrycznych wyrobu. Aplikacyjny charakter pracy dotyczy przemysłowej technologii uszczelniania powierzchni odlewów przeznaczonych na osłony wysokonapięciowych rozdzielnic napełnianych elektroizolacyjnym gazem SF_6. Materiałem konstrukcyjnym stosowanym do produkcji tego typu wyrobów jest stop aluminium w gatunku EN AC-42100 (Si 6,5 - 7,5 % mas., Mg 0,25 - 0,45 % mas.). Stopy te cechują się dobrymi własnościami odlewniczymi i mechanicznymi oraz zdolnością do obróbki cieplnej. Elementy uzyskiwane w technologii odlewania narażone są na niebezpieczeństwo występowania nieciągłości strukturalnych (porowatości, rzadzizny). Występujące w materiale porowatości mogą być powodem wybraków ze względu na wysokie wymagania dotyczące szczelności połączeń kołnierzowych.

1. Introduction

The steady progress of human civilization requires a continuous development of advanced materials as well as manufacturing processes in the broad area of metallurgy (alloy synthesis, processing, materials engineering etc.). One of the subject field of this development is a research on the manufacturing of Functionally Gradient/ Graded Materials (FGMs). Despite of the fact that the occurrence of these materials in nature have been known for thousands of years, their production, application and research on their properties were initiated only recently, i.e. at the end of the 20th century [1].

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The definition of a gradient material results from the character of its internal structure. In the most basic case, FGMs consist of two (or one) constituents of various functional characteristics like chemical composition, phase content, state of aggregation, structure etc. The differences in the material properties vary in its volume in a continuous or gradual way [1]. More precisely, the gradient materials are defined as materials with versatile functional properties intentionally obtained in the material and changing in a continuous way along, at least, one specific direction [2]. One of the factors identifying a material as an FGM one may be the presence of pores (internal voids). A gradual increase of their volume fraction, e.g. along the direction perpendicular to the surface of the material can result in different properties like impact toughness, thermal insulation, or relaxation of thermal stresses [1].

Metals may also be considered as functionally graded materials, however, in this case the variation in microstructure occurs usually across the surface layers. Manufacturing of various surface layers aims chiefly at surface hardening (the burnishing processes, thermal and thermochemical treatment), anticorrosive protection (aluminum coating) surface repair or improvement of the electrical or thermal properties of the material (Friction Surfacing). In the present paper a new method of producing gradient structures in metals is described. Also, some exemplary results of the research regarding its industrial application is presented. The goal of the research was to improve the surface quality in the mechanically treated (machined) aluminum alloy castings.

2. Methods of manufacturing metallic gradient materials

As was previously mentioned, gradient structures in metals may be formed mainly in layers near the surface. Manufacturing of different layers depends basically on a specific application and may comprise several methods. Producing a surface layer by burnishing technologies aims mainly at strengthening, smoothing and a technological treatment of the surface. A burnishing method is based on plastic deformation occurring in the outer layer of a material as a result of certain interaction (striking or pressing) of a tool (usually in the shape of a sphere, disc or a cylinder) with the treated surface. The plastic deformation reduces the surface roughness and thus improves dimension accuracy as well as work-harden the metal surface [3].

The thermochemical treatment, in general, is based on introducing structural changes by simultaneous thermal treatment and chemical interaction of the liquid in which the object is immersed. Depending on the purpose, the treatment results in surface hardening or increasing corrosion resistance. The reason of the change in properties lies predominantly in the adsorption of components (atoms) from the liquid and their further diffusion inward the material [4].

The creation of a gradient layer by padding relies on melting of an extra material (welding agent) on a surface and mixing it with partially melted base material. The general aim of padding is to regenerate the exploited parts (regeneration surfacing), manufacturing of materials with enriched outer layer in order to improve resistance to corrosion, abrasive wear, erosion, cavitations or increasing thermal and high-temperature creep resistance.

Yet another type of the process resulting in the development of chemical and structural gradient layers is Friction Surfacing in which various surface layers may be obtained on a metallic base. The Friction Surfacing consists in the introduction of the deposited material into the matrix by friction heating. The deposited material, in the form of a rod (called Mechtrod ^{TM}), is pressed, during rotational and forwarding motion, against the surface of the coated metal [5].

The described above methods of producing gradient layers allow for a number of improvements in the functional properties. The methods include work hardening or introduction of additional components which form alloys (phases) exhibiting a desired set of mechanical and technological features. Many products are not allowed to introduce additional components, which limits the application of the described methods. To a certain extent the interference in the structure of the material is made possible by burnishing, which, on the other hand, require specialized equipment (e.g. for ball peening) or specialized machines and instruments. In addition, introducing cold working generates the necessity of applying high pressure forces, which in turn, limits the application of this method to the tough and compact elements. Taking into account all factors considered above, the presented new technology allows for production of structural gradient materials without the necessity of introducing additional fusion welds and render capable of its application in typical technological conditions (typical facilities).

3. Surface hot working

The technology of gradient materials takes advantage of heat generated upon friction which influences the surface layer of the processed material. Unlike other technologies the proposed method combines a partial burnishing process with the Friction Surfacing method (or generally the Friction methods).

In general, the method of hot working (hot processing) involves spot heating of the surface of the processed material (in the place of contact between the tool and material) as a result of two simultaneous phenomena, i.e. friction and plastic deformation – both exerted by a rotated tool. The schematic representation of the process is shown in Fig.1 where the processed material (1) is deformed by the tool (4) attached to a fixture (2) with a clamp nut (3).

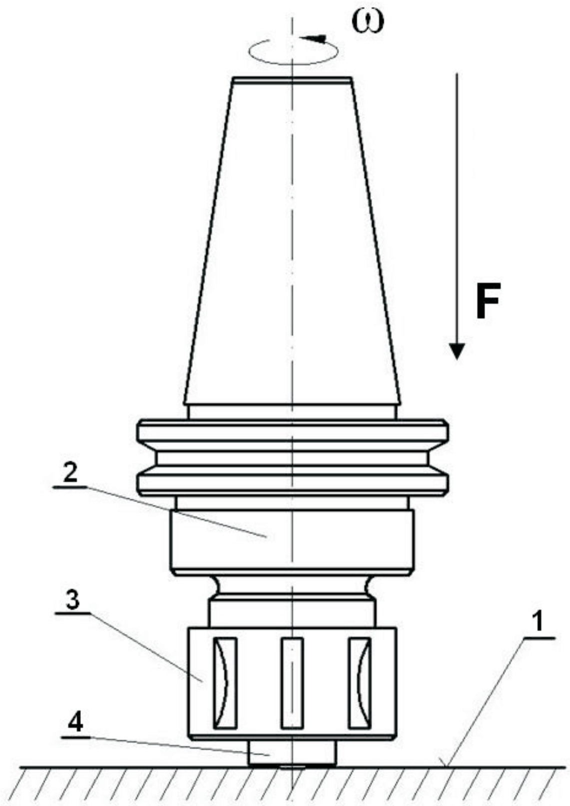

Fig. 1. Process diagram [6]

During the rotation of the tool the surface of the processed material undergoes hot working. This results in a considerable deformation of the layer near the surface (about several millimetres) and a slight indentation of the tool tip into the material (around 0.3 mm). The depth of indentation depends on the load limitations associated with the capabilities of conventional industrial equipment, in particular milling machines and machining centres CNC. The selection of optimal conditions for the surface plastic processing, including load, is realized by a design of the tool tip made usually of sintered carbides. During the process, the following technological parameters are controlled: rotational speed, depth of the tool penetration, rate of feed and temperature of the surface.

The process produces new microstructure on the surface of the material which is characterized by a fine and evenly distributed grains. This microstructure (the typical one is shown in Fig. 2) is characterized by higher hardness and higher density. Fig. 2 illustrates the continuous variation of microstructure on the section perpendicular to the surface. The continuous change in microstructure, on the other hand, leads to the variation of properties along the direction perpendicular to the burnished surface.

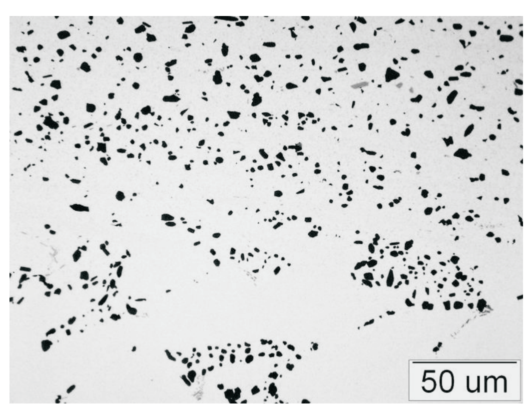

Fig. 2. Typical microstructure of the processed material

4. Example of application

An industrial application of the surface plastic processing has been illustrated in the case of improving the surface quality aluminum alloy castings designed for the casings of high-voltage switchgears filled with the SF_6 inert gas. The most important physical property of the SF_6 gas, regarding its insulating capacity, is its high dielectric resistance. Due to this feature the gas is utilized in extinguishing of electric arc in the medium and high voltage switches. The switchgears utilizing the SF_6 gas have superior properties compared to the conventional ones. The most significant advantages are: reduction of the field surface (10-20 times smaller), insensitivity to the working atmosphere, electric shock protection, lightning protection, fire and explosion protection. Additionally, the switchgears are characterized by simple maintenance and servicing. The main disadvantages of this type of switchgears is financial consideration (the cost of SF_6) and the occurrence of toxic gas dissociation produced during the electric arc extinguishing, which requires tight flange joints of the cooperating elements made of aluminum alloys in the technology of sand casting.

Considering the fact that the production of castings in sand molds utilizes alloys of a wide range of solidification temperatures, the microstructure of the cast products may contain some structural discontinuities (shrinkage, porosity). The occurrence of flaws on the joining surface in the material after mechanical machining is the main reason for the cast disqualification and rejection by a quality control. The high quality requirements are specified by the appropriate standards [7, 8] to ensure the lack of porosity or shrinkage on the surface of the casting, especially in the flange joint area (thick line in Fig. 3). Additionally, the standard specifications do not permit fixing flange surfaces by welding or an application of chemical-hardening agents.

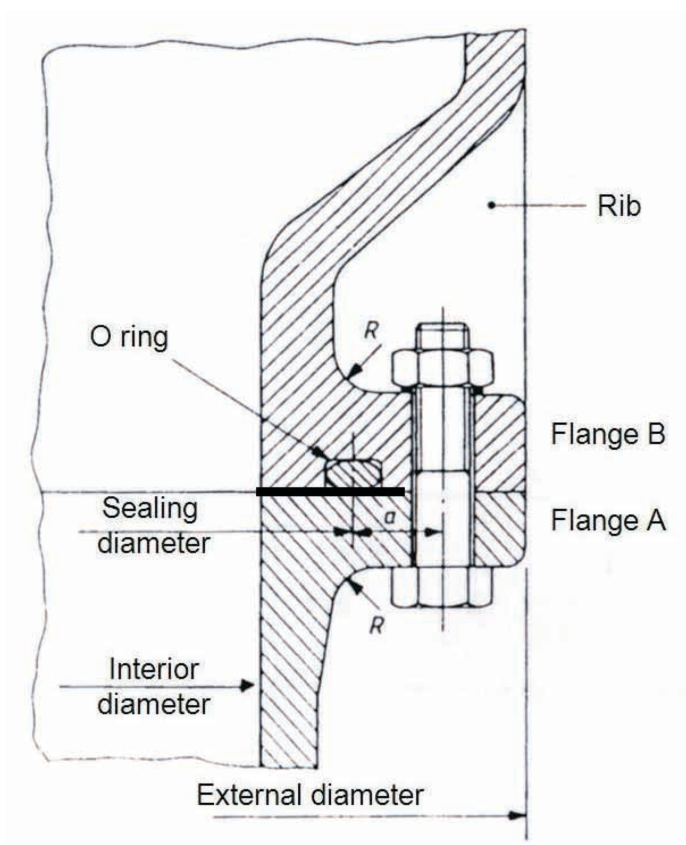

Fig. 3. View of flange joint in switchgear [7]

Considering these reasons, testing of the properties of the internally faulty materials and developing a technology for repairing the faulty casts is of crucial importance due to both technological and economic considerations in the production of castings designed for the advanced products.

5. Selected laboratory test result

The issue of tightness of flange joints in high-voltage switchgears described above indicates a possibility of utilizing the newly developed method for the surface plastic processing/working. The targeted alloy anticipated in such application is an AlSi7Mg0.3 alloy. The alloy belongs to the silumin group of alloys of the hypo-eutectic AlSi-type alloys. The most common representatives of this group of alloys are AlSi5Mg, AlSi7Mg, AlSi9Mg, and AlSi10Mg. This alloy is in fact composed of three elements, i.e. aluminum as a matrix, silicon, and additionally, magnesium. Magnesium in this alloy forms the Mg_2Si phase which improves considerably mechanical properties by solution treatment and further ageing. The detailed chemical composition of the tested alloy is given in Table 1.

TABLE 1

Chemical composition of AlSi7Mg0.3 alloy [9]

Chemical composition, wt %									
Si	Fe	Cu	Mn	Mg	Zn	Ti	other		Al
							each	total	
6.5 – 7.5	0.19	0.05	0.10	0.25 – 0.45	0.07	0.08 – 0.25	0.03	0.10	rest

Because silicon content is lower than eutectic composition (12 rot %) the range of solidification temperature increases and, as a consequence, the occurrence of porosity is more likely. The influence of solidification time and modification type on the occurrence of porosity is shown in Fig.4.

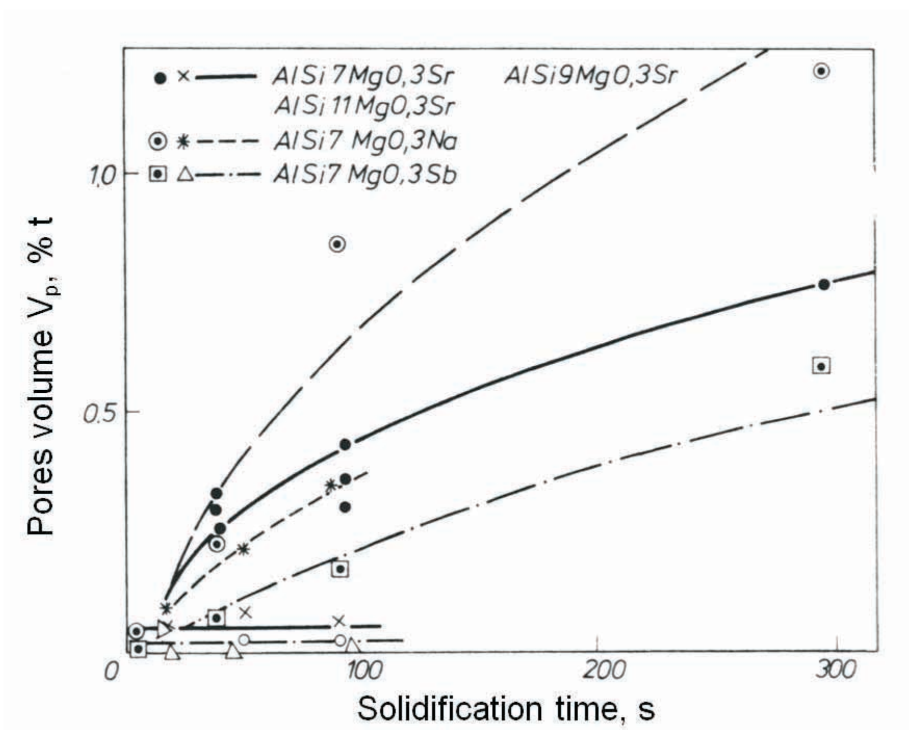

Fig. 4. Dependence of the volume fraction of on on solidification time and type of modifier [10]

However, in order to find and select optimal conditions for surface processing of the AlSi7Mg0.3 cast alloy by hot working, the laboratory research was conducted on several samples excised form an EN AC-42100 aluminum alloy. The research was aimed at improving the leak tightness of the alloy by the integration of its internal discontinuities. The compression tests on cylindrical samples 5 mm in diameter and 5 mm high were performed within the temperature range of 20 – 400°C.

The results allowed for the analysis of the influence of the rate and temperature of deformation on the magnitude of load imposed during compression. Flow curves of the material have been recorded in the load-deformation coordinate system, which enabled a direct determination of the necessary force required for the process. Additionally, tests have been carried out in order to find out if the simulated internal discontinuities can be welded during this process. For this purpose, cylindrical samples of 5 mm in diameter and 5 mm high have been also compressed. However, in order to simulate the internal faults, inside each sample (perpendicular to the side surface) holes of 1mm in diameter have been drilled. The effect of holes welding was assessed on metallographic sections. The examined region was located on the sample surface and include the area perpendicular to the axis of an hole.

Fig. 5 to 7 show selected results of the compression tests carried out on samples without holes. The samples were examined in the selected range of temperatures for individual deformation rates 0,1 s^{-1} in Fig. 5, 1 s^{-1} in Fig. 6, and 10 s^{-1} in Fig. 7 [11].

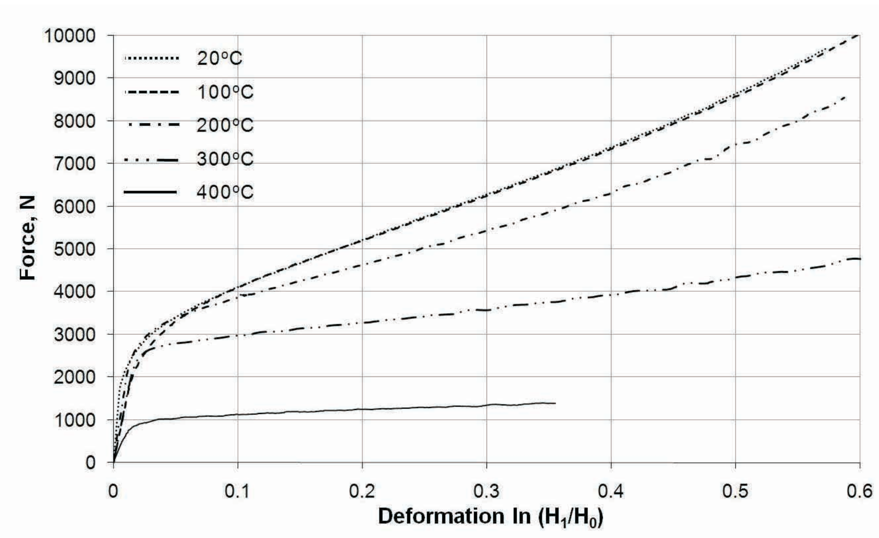

Fig. 5. Flow lines. Deformation rate 0.1 s^{-1}

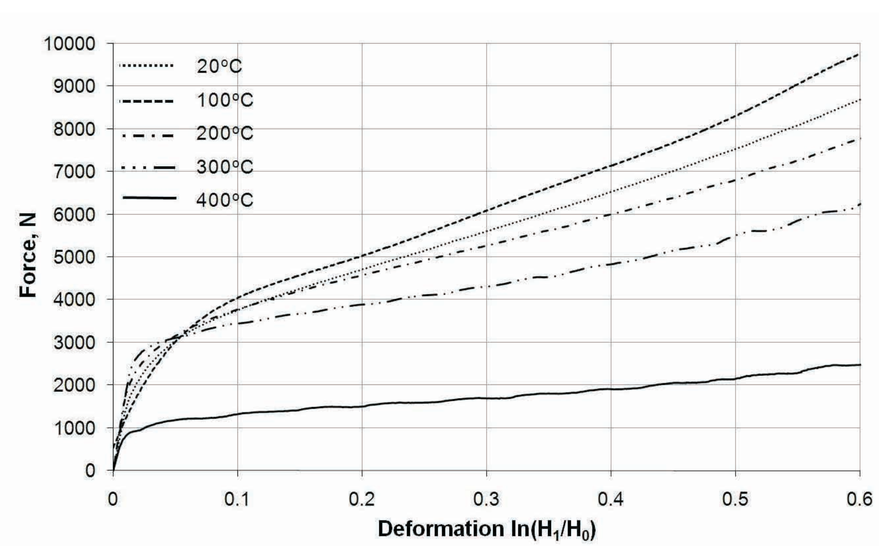

Fig. 6. Flow lines. Deformation rate 1 s^{-1}

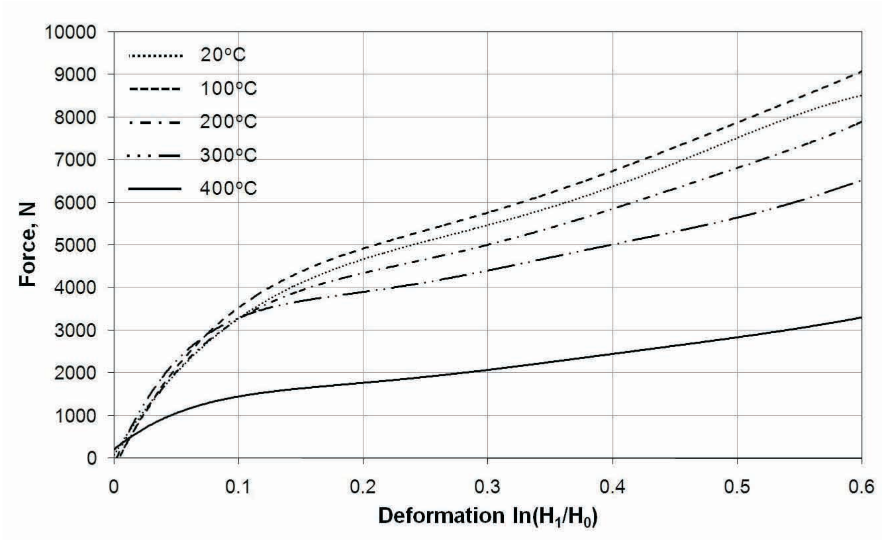

Fig. 7. Flow lines. Deformation rate 10 s^{-1}

The selected results of compression tests carried out on samples containing holes together with a curve for the test at 20°C are shown in Fig.8, whereas the microstructures of the welded area around the opening (at 250°C compression temperature) are shown in Fig. 9.

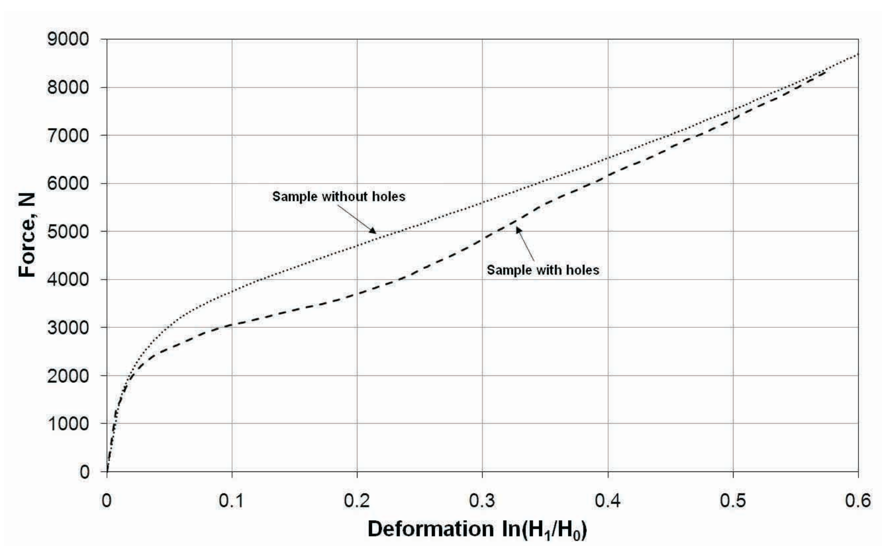

Fig. 8. Compression curves for a sample with and without an opening at 20°C

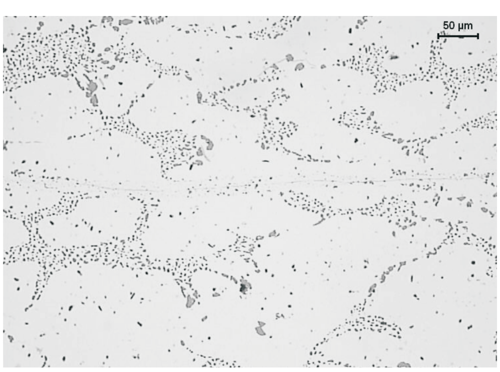

Fig. 9. Microstructure of the opening area; sample 250°C – zoom

In sum, the results of the laboratory tests showed that the parameters of deformation analyzed during compression tests of the alloy EN AC-42100 are satisfactory from the malleability point of view. The increase in temperature of deformation considerably decreases the force required for deforming samples. The compression tests conducted on samples with simulated material faults showed that material discontinuities like porosity can be removed by plastic processing.

6. Industrial testing

In order to conduct industrial tests a preliminary selection of technological parameters, i.e. rotational speed of the tool and compression force, was performed. An appropriate selection of rotational speed allows for predicting the desired temperature in the place of deformation. For this purpose, out of a number of available equations describing the correlation between an temperature increase and the friction the authors used the equation proposed by Archard [12] The equation calculates an average increase in temperature (T_{AV}) by taking into account the tool rotation speed (slide) and plastic contact in the area between the material and the tool,

$$T_{AV} = \frac{\mu(\pi p)^{\frac{3}{4}} N^{\frac{1}{4}} \upsilon^{\frac{1}{2}}}{3,25 I_c (\lambda \gamma C_p)^{\frac{1}{2}}}$$

where:
μ – friction coefficient of 0.5
p – stress equal to yield stress
N – load
υ – slide speed
I_c – mechanical equivalent of heat = 4,1868 J/cal
λ – coefficient of thermal conductivity
γ – density
C_p – average specific heat

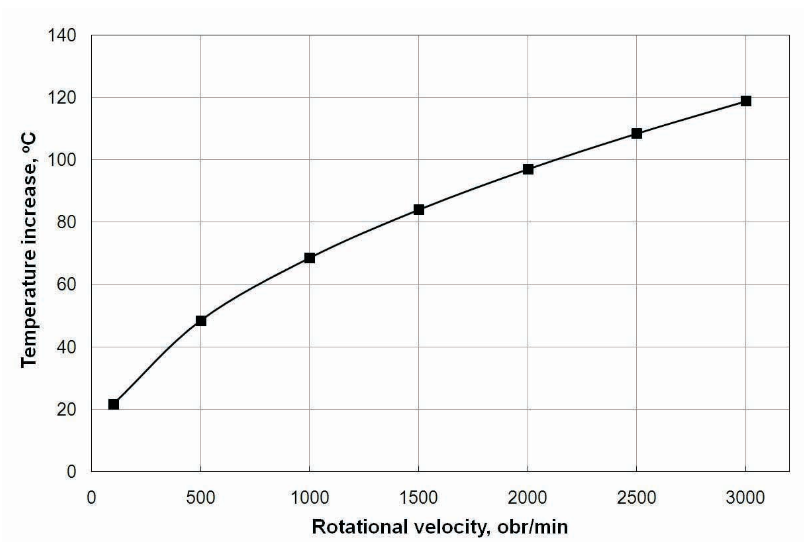

Fig. 10. Influence of rotational speed on the temperature increase

For the assumed values of the surface plastic processing, considering properties of EN AC-42100 aluminum alloy, a curve showing the correlation between the temperature increase and tool rotational speed was determined (Fig.10). Based on the calculations and the permissible parameters of tool performance, the rotation speed was set at 2000 – 2500 rev/min. The selection of load was determined by experiments directly at a work station. The test was done by static indentation of the tool against the surface of the material at ca. 20°C. The obtained results served as a basis for the calculation of the maximum force in the process. The correlation between the indentation force and the indentation depth is shown in Fig.11. Based on the conducted experiments and the capacity of the industrial tool, the load was set at 6-7 kN, which resulted in a value of depth of 0.3 mm.

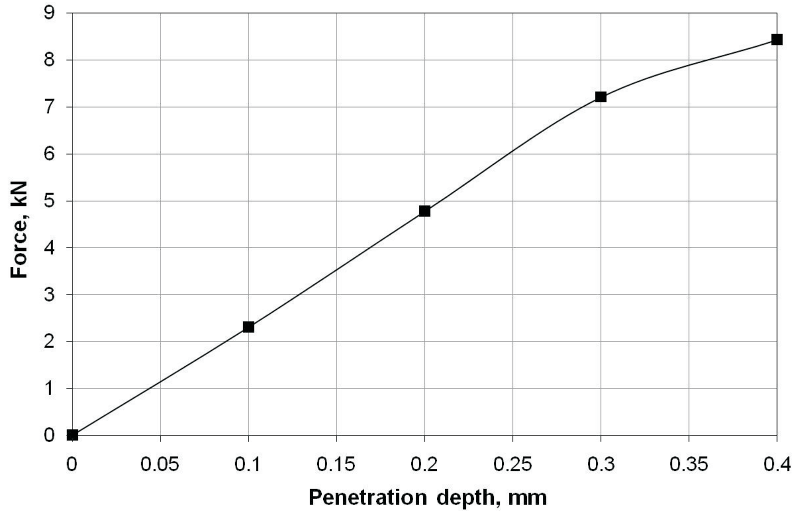

Fig. 11. Experimental correlation between the load and indentation depth of a tool

Industrial testing was conducted on the basis of the selected parameters of the surface plastic processing. For this purpose, a casting, in the form of four-pole piece, was mounted in the processing facility and initially processed at the place of flange connection. The treatment created a surface which was uniform and perpendicular to the body of the tool used for the deformation process. Because of satisfactory results, the process was continued on the entire surface of the connection flange. During the experiment, the process parameters like speed of feed, tool rotation and the distance between tool paths were altered. The detailed technological parameters are shown in Table 2.

TABLE 2

Parameters of technological testing

Parameter	Unit	Test No				
		1	2	3	4	5
Head revolution	**rev/min**	2000	2000	2000	2500	2500
Head feed	**mm/min**	200	150	150	200	300
Feed	**mm/rev**	0.1	0.075	0.075	0.80	0.12
Distance	**mm**	4	4	4	6	8
Depth of strain	**mm**	0.3	0.3	0.3	0.3	0.3
Temperature	**°C**	–	213	219	185	100

After the process completion, longitudinal samples were excised from the deformed elements. The samples were subjected to the metallographic examination. The material microstructure formed during the process is shown in Fig. 12. The deformed zone, about 1mm thick, can be easily distinguished from the primary cast microstructure inside the material. Both regions are separated by an intermediate zone where the microstructure changes in a continuous way from deformed to the cast one. In order to determine the influence of the tool on the properties of the material, indentation hardness was measured by the Brinell method. The results are shown in Fig. 13.

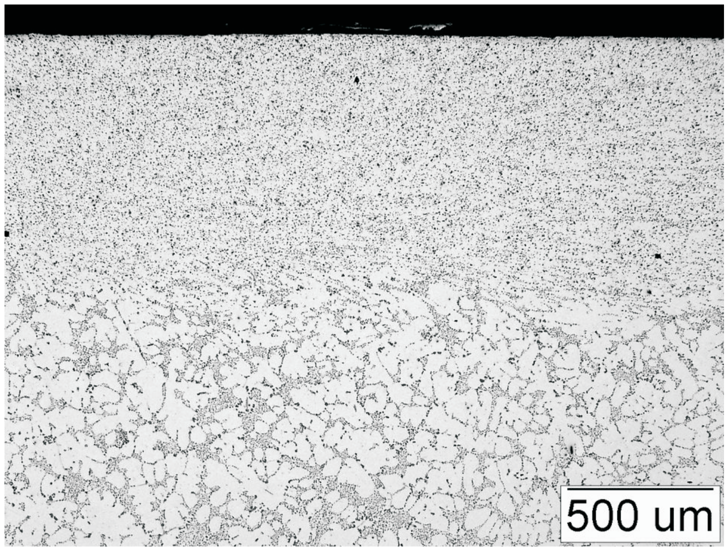

Fig. 12. Microstructure of the processed material

The hardness of the deformed layer is lower than the hardness of unprocessed material. The change in hardness was detectable up to the depth of 5 mm.

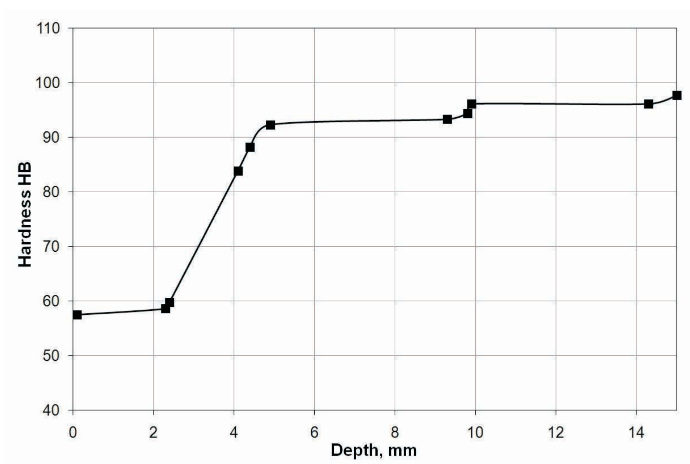

Fig. 13. Dependence of hardness on the distance from the surface of the processed material

7. Summary

Laboratory testing and industrial testing of the material with structural gradient have confirmed possibility of industrial application of the proposed technology. The produced surface layer was free from any discontinuities and its microstructure changed in a continuous way from the microstructure typical for the deformed material to the microstructure typical for castings. The proposed technology has evidently a significant advantage over other methods since it shows a possibility of the modification of the material surface without a need of introducing additional materials. The quality of the produced layers are sufficient for the elimination other materials like welds or seals. An additional advantage of the process is a possible application of the method herein described on standard processing tools (milling machines, lathes, or processing units).

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