MANUFACTURE OF LIGHTWEIGHT COMPONENTS FOR A COMPOSITE PROTECTIVE ARMOUR USING SQUEEZE CASTING TECHNOLOGIES

Abstract. Experimental studies described in the present article adapt modern VSC 500 equipment produced by UBE for the squeeze casting technology, located at Foundry Research Institute in Cracow, Poland. The aim of such adaptation was to set up a comprehensive technology capable to manufacture essential elements for lightweight composite armour protection. The overall scope of the study included development of basic design of an armour element and the selection of materials necessary for its construction. Furthermore development of special mould design along with determining the optimal parameters for the squeeze casting process has been considered. The presented unique liquid-phase technology of composite element manufacture allows obtaining armour elements with a high protection efficacy against small-calibre armour piercing projectiles. The elements can also be part of a modular protection system for mobile transport means (land and aerial vehicles).

Keywords: squeeze casting, composites, light metal alloys

1. INTRODUCTION

Modern armour systems, irrespective of their ballistic resistance, should in the first place meet criteria that are related to weight decrease, which is particularly important in the context of protection of unarmoured objects, such as aerial transport means, and of armoured objects, such as wheeled carriers, tracked platforms, etc. The material used in traditional monolithic armour was rolled steel of high hardness. However, the introduction of very effective warheads with special cores had a great impact on the development of more efficient armour and forced engineers to use new materials. The most impressive progress was made in the area of lightweight composite armour, where the key factor, in addition to ballistic resistance, was the lowest possible weight. It was found that in the case of vehicles protected by means of heavy armour, the cost of fuel used increased highly and also the risk of being hit increased because of the reduced mobility.

New generation of lightweight, usually composite (metal and ceramic) materials used for constructing high performance armour required developing new and innovative manufacturing processes. These processes usually are the result of current development trends in the various branches of industry, including the defence industry, and of local and international economic and social conditions. In the case of composite materials the processes applied include adhesive bonding of sandwich boards, welding of rolled sheet, pressing of polymer, metal and ceramic layers at elevated temperatures, forging and casting.

Casting is the most cost-effective method of final shaping of metal products and metal-containing composite materials. It allows forming parts of complex shape and high surface area. The basic disadvantage of casts obtained using traditional processes, as compared to parts made using plastic working processes, are their inferior mechanical properties. These are caused by the casting structure of the material (large grain size, porosity...
and other defects). Moreover, the surface defects that occur in castings, such as hot tears and cold shuts, may lead to formation of cracks in the casting structure during its use, substantially reducing thereby its lifetime. Pressure die casting, where increased pressure is applied to quickly fill the mould with liquid metal, is used increasingly in the production of light metal castings. This process is applied mainly in the high volume production of castings of complex shape, thin walls, and weight of up to a dozen or so kilograms [1]. An increasing number of precision and critical machine parts are made, where stringent strength requirements dictated by the aviation, automotive and defence industries have to be met. Pressure die casting, as opposed to gravity casting, is a virtually waste-free process. The main drawback of pressure die casting is the high cost of mould production, which involves drawing up technical documentation with necessary calculations and drawings that reproduce the shape of the product, developing simulation of the mould filling process and the complex process of constructing the mould using advanced machining techniques. The disadvantage of pressure die castings is their lack of resistance to elevated operating temperatures due to the so-called gas porosity, the occurrence of which is associated with the shutting up (occlusion) of gas bubbles inside the casting, usually as a result of turbulent melt flow in the melt delivery system and inside the mould. Therefore the main parameters that have an effect on the proper structure of the casting include: recovery rate of air from the mould, rate of filling the mould with molten metal, pressure intensification time and the geometry of the inlet chamber, of the inlet and venting systems [2].

Squeeze casting is generally classified as one of die casting processes. As opposed to pressure die casting, where turbulent molten metal flow occur, in the squeeze casting process the metal fills the mould in a laminar manner, with no turbulence, at a much slower rate, and there is no gas occlusion in the casting. In classical terms, the squeeze casting technology involves pouring molten metal into the mould cavity heated beforehand and with a protective and insulating coating in place, followed by exerting pressure by means of a plunger (punch). Pressure is exerted onto the molten metal immediately after charging the mould (to minimise formation of any solid phase) and maintained throughout the whole process until the casting solidifies entirely. After a predetermined time the casting is pushed out of the mould by the ejector system.

High pressure, under which the metal solidifies in the mould cavity, promotes formation of castings with minimum defects, with no structural imperfections, which in turn enables further complete thermal processing (improvement), in particular high-temperature dispersion hardening [3]. The application of external pressure, both as force factor and as a thermodynamic factor during metal solidification, the final strength properties of the castings may be substantially improved [4]. That external pressure improves the processing features of the molten metal, i.e. it intensifies the ability of the latter to fill the mould cavity and reduces its contraction. There is also another known effect of the increased pressure on the casting: increased casting compactness as a result of eliminating shrinkage porosity and gas porosity. Gas porosity in a casting is determined by the conditions of gas bubble nucleation in solution, and the high value of external pressure makes gas bubble formation practically impossible [5]. Whereas the heat exchange that occurs in the casting-mould system under the conditions of squeeze casting leads to castings with no structural discontinuities and with fine microstructure and of high performance close to that of products manufactured using plastic processing methods. However, the squeeze casting process, as compared to plastic processing methods, is in many ways more economical, for instance in terms of energy and material consumption. Squeeze cast products have, on the average, 10 to 15% higher yield strength, and by 50 to 80% better percentage elongation. The squeeze casting technology allows achieving near-net shapes of the castings and metal yield of over 95% [4-6]. The technology
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is used for manufacturing critical components for the automotive, aviation and armaments industries. Its advantages have been appreciated in the context of the manufacture of suspension components subject to loads in cars of many prominent makes.

2. TECHNOLOGY OF METAL COMPOSITE MATERIALS FOR DEFENCE APPLICATIONS

When squeeze casting is applied to cast metal matrix composite materials, the external pressure promotes compatibility of the metal/reinforcement system components during crystallisation (e.g. ceramics, fibres, special reinforcing structure) [7-8]. In the case of squeeze infiltration the applied pressure enables flow of the molten metal into capillary canals of ceramic preforms (Figs. 1, 3) or interstices between the elements of reinforcing structure or of 3D textile and formation of a web of interpenetrating components.

Fig. 1. Preform made of Saffil fibres and CT analysis
a) general view, b) CT reconstruction
Fig. 2. Squeeze infiltration effected as squeeze casting with external pressure applied by means of an overhead pressing ram

Squeeze infiltration (Fig. 2) is probably the most cost effective and versatile process of obtaining composites with light metal alloys. The advantages of the process include relatively low cost of matrix material, reduced risk of mechanical damage to the reinforcing material, high rate of manufacture, simple tooling (similar to conventional casting), and the ability to obtain net or near net shape, avoiding thereby the need for extensive machining or finishing. Other advantages are the result of limitations of chemical nature: shorter contact times and, consequently, reduced interaction between reinforcement and matrix. In the case of squeeze infiltration the occurrence of unfilled parts is much reduced, as the molten metal matrix fills the porous areas of the preform or the voids of the reinforcing structure under pressure and under controlled conditions of temperature distribution, which ensures obtaining a fine-grained microstructure. The main disadvantage of the process are higher requirements on tooling and pressure generating equipment. Problems also occur in the case of large or locally reinforced castings. The following process parameters have to be carefully controlled:

- initial temperature (and its distribution) of the preform, mould and metal,
- volumetric fraction of the reinforcement,
- value of the pressure applied and infiltration rate (one of these parameters depends on the other) [9].
Prefabricated ceramic preforms (Figs. 2-3) are placed in the mould, often together with appropriate inserts or cores. The location of preforms depends on the intended needs for local or overall reinforcement of the product. Gas that accumulates in the preform in front of the infiltrating metal is usually removed through vents in the mould. The preform temperature should be higher than the liquidus temperature of the matrix in order to reduce segregation of the structural components of the matrix. It is also important that the temperature distribution in the preform is uniform (Fig. 4), and the time between heating the preform and infiltrating it is as short as possible, as this prevents undesirable deformation which affects future properties of the products. Preforms are usually initially heated in furnaces or by means of special radiation heaters. Sometimes the low temperatures of the preform and of the mould, in combination with high pressure values at the end of the cycle, minimise the undesirable interaction between reinforcement and matrix.

Fig. 3. Ceramic preform

a) Reconstruction (3D visualisation) of a Mullite preform, b) spatial distribution of defects

Fig. 4. Thermal analysis of the infiltration process – temperature distribution in the preform immediately prior to infiltration. (Preform of Saffil - infiltrated with the melt – 7075)
Table 1. Basic information on ceramic preforms

<table>
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<tr>
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<th>Material</th>
<th>Preform type</th>
<th>Porosity, % vol.</th>
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<tbody>
<tr>
<td>1</td>
<td>Silicon carbide (SiC)</td>
<td>Particles</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>Carbon fibre</td>
<td>Whiskers</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>Boron carbide (B₄C)</td>
<td>Particles</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Alumina (Al₂O₃)</td>
<td>Whiskers</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>Mullite (Al₆Si₂O₁₃)</td>
<td></td>
<td>75</td>
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3. OBJECTIVE

Developing a technology of modular armour manufacture includes selecting materials of appropriate mechanical properties to meet the criteria of applicability for the defined purpose. As part of MODPANC project execution, materials were selected to construct a new generation of modular armour designed for protecting vehicles. The first stage of the task comprised acquisition or obtaining these materials using metallurgical methods. Metal alloys were selected mainly by taking into consideration their suitability for squeeze casting, and also their strength and other properties, such as: rigidity, plasticity, impact resistance and physical and chemical properties, corrosion resistance in particular. The main step was the adaptation of a modern squeeze casting station (UBE VSC 500) at the Foundry Research Institute to the needs of a comprehensive manufacturing process of innovative cast modular armour. The scope of work included design of the armour, of a special pressure mould, selection of special alloys, determination of squeeze casting parameters. The formed armour castings were tested for the presence of casting defects and various structural discontinuities in order to determine the effect thereof on the performance of the finished products, and to determine the phenomena occurring as a result of applying mechanical load.

4. TOOLS

Originally the squeeze casting of basic components was carried out using an upgraded hydraulic press PHM-160 (Fig. 5b) capable of providing maximum pressure of 150 MPa and mould clamping force of 160 t. The pressure mould (Fig. 5a) had a system of cooling ducts for temperature stabilisation and distribution throughout the volume of the mould. Composite castings with the dimensions of diam. 100mm x 100mm were produced with a ceramic plates of various thicknesses placed within it, depending on the applied method of infiltration (top or bottom). The scheme of pressure infiltration is presented in Fig. 1. Ceramic preforms were saturated with several types of light alloys, based mainly on aluminium and magnesium.
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**Fig. 5.** Mould and station for casting metal matrix composites using an upgraded PHM-160 press.

a) special pressure mould, b) hydraulic press

**Fig. 6.** View of ingot removed from mould and of finished composite panel after milling

a) ingot removed directly from mould, b) composite panel after milling

At present most of the tests of squeeze casting are conducted on a versatile station UBE VSC 500 (Fig. 7) installed at the Foundry Research as part of project ZAMAT execution, partly funded by the EU. The device, with a vertical feeding and clamping system, is fitted with a melting and heating furnace having a 500-kg capacity pot for preparing the desired metal alloys. The UBE VSC 500 squeeze casting station has a clamping force of 500 tonnes; ram speed is within 10 to 80 mm/s, whereas maximum force $F_t$ applied by it is equal to 80 t. These specifications are sufficient for proper manufacture of an armour component casting. The machine is fitted with modern control system and software enabling accurate and immediate data acquisition. The machine is prepared by installing a specially designed casting mould in the clamping unit of the machine, connecting the heating/cooling fittings, and launching the control program. Then a specially prepared preform or internal structure of the armour along with ceramic parts are placed in the mould into which molten metal is delivered. The subsequent step is initial casting performed to determine machine operating parameters,
chamber capacity, volume of metal, mould cooling and heating temperature, metal feed rate and ram force. The proper cycle of forming a finished casting using this machine comprises four stages. The first consists in taking molten metal from a special melting and heating furnace by means of an operating arm with a ladle on its end, followed by pouring the metal into an inclined inlet chamber. In the third step the chamber is positioned upright, after which, in the fourth step, the mould is filled with molten metal by means of the moving ram, and squeeze infiltration proceeds. After the mould is filled with the metal, the casting is pressed by the ram. A series of test armour castings can be used for field tests to determine the actual protective capability.

Fig. 7. UBE VSC 500. A versatile stand, a rarity in Central Europe, for squeeze casting.

The mould for squeeze casting operates under extreme conditions. High pressure, high temperature, and corrosivity of the molten metal in relation to mould material are the most important problems faced when designing this casting tool. Based on many years of experience in squeeze casting and squeeze infiltration of porous materials of the employees of the Foundry Research Institute, a preliminary design was drawn up, followed by complete design documentation of a mould to be used on the UBE VSC 500 stand (Fig. 8c).
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Fig. 8. Special pressure mould for squeeze casting
a) upper half of mould with a representation of the shape of the basic armour element
b) demonstration of mould design – lower half

Mould consists of two parts (Fig. 8). A special insert is placed in the lower part. The insert may contain preheated inserts or special reinforcing structures designed for squeeze infiltration with molten metal. The upper moving part holds a pressing ram. Both parts of the mould have cooling ducts that enable temperature control of the mould during casting. The external heating and cooling system enables temperature stabilization during casting, and is also used for preheating the mould prior to starting the casting process and during short breaks necessary to mark samples or to X-ray the castings. The mould can be heated up to 350°C, which is beyond the temperature range applied in conventional solutions. Preforms are preheated by means of high output infrared heaters.

As part of MODPANC project execution, different variants of the basic armour element are now manufactured. In future that element will form part of additional modular armour of wheeled carriers and tracked platforms. The element may comprise internal reinforcing structure consisting of sheets or foil of increased strength and ceramic blocks, and external structure in the form of a matrix of light metal alloys (Figs. 9a, b).

Fig. 9. Representation of conceptual design of the basic armour element to be implemented under the MODPANC project
5. SUMMARY

The passive composite protective armour, designed according to original engineering ideas at the Foundry Research Institute is composed of a special multilayer structure buried in a metal matrix of light alloys which augments the strength of the composite material. Such a solution provides high protection efficacy against small-calibre armour piercing projectiles and may be part of external shell of the protection system for mobile transport means. This unique armour design and manufacturing method based on squeeze casting makes the armour of this type strong and obviates the need to conduct costly and time-consuming finishing operations. Adoption of appropriate research methodology will allow verifying whether the proposed variants of the armour and method of its fabrication ensure that the product meets the requirements specified in standards for the application of additional modular armour. The most important component of the methodology will be the versatile UBE VSC 500 squeeze casting station, used for carrying out all casting tests, and its adaptation will consist in determining optimal process parameters to ensure high quality and repeatability of products.

Advantages of the squeeze casting process open up new design possibilities of additional armour systems consisting of cast components, as this process is in fact an alternative to traditional casting technologies and plastic working processes. The process itself is easy to conduct, economically sound, virtually waste-free (with high molten metal yield of even more than 95%) and it warrants high production output. Of all casting processes squeeze casting provides the highest level of mechanical properties and maximum fineness of the structure which, in combination with its technological integrity, allows critical applications, such as for heavy duty parts, as well as for protective elements in the form of armour systems.

6. REFERENCES

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