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METAL MATRIX COMPOSITES FABRICATED BY THE SQUEEZE CASTING PROCESS

ABSTRACT

In this study the theoretical and practical aspects of the application of external pressure in fabrication of metal matrix composites, especially by the squeeze casting process, were discussed. Depending on the type of the metal liquid and of the reinforcing phase, a few schemata of the solidification process under pressure were proposed, illustrating each one of them with some data on the properties, structure, and method of fabrication. Numerous own design and engineering solutions used by the Foundry Research Institute in Kraków for fabrication on a laboratory and semi–industrial scale of composite materials with non–ferrous metals alloys used as a matrix were disclosed. The possible areas of application of metal matrix composites and the related economic aspects were considered. The study is the first attempt in Poland at a complex approach to the problem of application of the squeeze casting process to fabrication of a new family of the engineering materials.

INTRODUCTION

Every composite consists of a matrix (metallic or non–metallic) and a reinforcement phase, also called component, which may assume the form of a dispersed phase, a dispersed–continuous phase, and a continuous phase. Among the metal matrix composites, the cast metal matrix composites (CMMCs) characterized by the presence of a liquid phase (metal matrix) throughout the whole process of their fabrication, are gaining a wide–spread popularity.

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If, throughout the whole cycle of manufacturing, the reinforcing phase remains in the solid state, the composites are called composites *"in vitro"*, but if both components are solidifying from a liquid phase, the composites are called composites *"in situ"*. In the case of cast metal matrix composites, practically almost all of these materials are included into the *"in vitro"* group. The group of the *"in situ"* composites comprises the materials obtained under the conditions of either directional solidification or through direct chemical reaction in a bath of liquid metal, resulting in the formation of a reinforcing phase, usually in the form of dispersed particles of a solid phase *(endogeneous composites)*.

The metal matrix is reinforced in order to obtain the high functional and performance characteristics of the composites, unattainable by the common methods of changing the structure in monolithic products [1]. Depending on their future application, various requirements are imposed onto the cast metal matrix composites: high strength (under various conditions of force–temperature–time loads), high abrasion resistance, good sliding characteristics (for performance in slide bearings), or other special performance characteristics.

The research studies on the methods of making CMMCs were probably started in the mid–sixties when the nickel–coated particles of graphite were introduced in the stream of argon into a liquid aluminium alloy [2]. The next step were the attempts at obtaining a composite of aluminium–alumina by stirring of the melt [3]. Those research works can be regarded as a beginning of the creation of a group of new materials called particulates reinforced cast metal matrix composites or cast metal–matrix particulate composites (MMPCs). Speaking about the events which gave origin to the creation of metal–matrix composites one can mention the fact that much earlier some research studies had been devoted to the metal–ceramic systems, in which the role of "a reinforcing phase" was played by the non–metallic inclusions, whose presence was otherwise considered to be of a destructive nature in the process of obtaining the required properties of the manufactured monolithic products.

At the beginning of the seventies, to enhance the viscosity of the liquid matrix and to reduce the effect of the particles flotation or settlement, some attempts were made to introduce the particles of Al_2O_3, SiC and TiC to a liquid–solid aluminium alloy [4]. The process was called "compocasting". The research initiated further development of the casting technologies which consisted in joining together the composite components in a range of temperatures of the beginning and end of the solidification of a metal matrix [5] which, containing the required volume of a liquid phase, made the application of techniques used in the presence of liquid phases possible. The next logical step was the development of a bottom pouring technique [6].

The metal matrix composites are assumed to be used for the first time in Japan in 1982. According to the available data in literature, TOYOTA MOTOR CORPORATION demonstrated a composite aluminium piston with reinforcing insert made of alumina fiber to be used in a Diesel engine [7]. It was the first industrial application of squeeze casting to obtain a CMMC (Fig.1), although earlier applications of this technology in military and aerospace industries believed to be also possible. When composite materials became the centre of growing interest, almost immediately the technology of casting occupied a priviledged position as a method of their fabrication [8–15]. During the last few years the following trends have been observed in this field:

– introduction of particles, whiskers or short fibres into liquid metal, obtaining a homogeneous suspension, and gravity or pressure die casting of this suspension in different ranges of temperature,

– infiltration of liquid metal into the previously prepared preform and its solidification with application of various methods stimulating the quality of the obtained product,

– making composites "*in situ*", basing on thermodynamic reactions in metal liquid, resulting in the formation of a reinforcing phase in the form of ceramic compounds, intermetallic compounds, particles, or even whiskers (e.g. XD process [13]).

Table 1 gives a short history of the development in metal matrix composites till the end of the eighties [12].

From the research done until now it follows that in cast composites the following materials can be used as their matrix: iron and its alloy, numerous non–ferrous metals and their alloys, mainly aluminium, magnesium, tin, lead, nickel and titanium. In the case of aluminium the most popular matrix materials are the following alloy systems:

- Al–Si (A356, A357, A359)[1],
- Al–Cu (A201, A2014, A2618, A2124),
- Al–Si–Cu (A339, A380),
- Al–Zn–Mg (A7075, A7049, A7090).
- Al–Mg (A6061, Al–Mg_2Si),
- Al–Li (A8090).

The reinforcing phase are particles, whiskers, "short fibres and continuous fibres" of graphite, carbon and its chemical compounds from the family of oxides (Al_2O_3, SiO_2, ZrO, TiO_2), carbides (SiC, TiC, B_4C), nitrides (Si_3N_4), and borides [18–43], MICRAL[2], mica or flyashes (microsphere, cenosphere) are also used [22–39]. Apart from the basic alloying additions, some auxiliary materials are added to either promote the wettability of the matrix–component system (e.g. lithium in Al/Al_2O_3 or Al/SiC systems, titanium in an Al/C system) [40], or – vice versa – to block an interaction between the composite components with simultaneous modification of the oxide film on the surface of metal (e.g. magnesium, lithium or calcium added to aluminium reinforced with oxidized SiC). Then, the reinforcing phase is oxidized, or copper, nickel, or chromium coated, or treated with some salt solutions [41].

The unfavourable effect, encountered most often during metallurgical processing of commercial Al/SiC composites, is the probability of formation of aluminium carbide.

The alloying elements and auxiliary materials, the type of the reinforcing phase and the method of its processing as well as an optimization of the temperature – and

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[1] After ASTM.

[2] The trade name of a reinforcing phase [Al_2O_3–SiO_2 (mixed oxides)].

time–related parameters should be chosen taking into consideration the results of wettability testing of a matrix–reinforcing phase system, and the results of an analysis of the kinetics of dissolution, formation and decomposition of chemical compounds. So, the process of fabrication of cast composite materials consists in obtaining a permanent combination of the composite components. The ability to form this combination is called physico–chemical compatibility: thermodynamic and kinetic. In practice, only a few systems of the type metal matrix–reinforcing phase are able to form the compatible thermodynamic couplings. Hence, quite logical seems the attempt to create such conditions of temperature, force and time which will satisfy the requirements of kinetic compatibility, i.e. the compatibility encountered during the process of fabrication [42]. To achieve this goal the following technological operations are performed:

1) affecting the composite components matrix (optimization of the set of alloying additions, the use of ultrasounds, of electromagnetic field, etc.) and reinforcing phase (radiation, field of force, etc.),

2) the use of technological or barrier coatings, applied onto the reinforcing phase, and thermal activation,

3) pressure activation, covering the whole set of the interrelated and concurring phenomena, whose driving force is the thermodynamic reaction in a system subjected to the effect of external pressure.

The external pressure can play the role of not only a very effective factor promoting changes in the metal structure and behaviour, but it can also act as a very important stimulator, generating in CMMCs the required interaction between the liquid (liquid–solid) matrix and the reinforcing phase. With causative factor distinguished and the pressure value subjected to variations, the methods of fabrication of the cast metal matrix composites can be classified together with other casting processes using pressure (Table 2). Among these methods the squeeze casting process is now one of the leading and most promising means of CMMCs fabrication.

SQUEEZE CASTING OF METAL MATRIX COMPOSITES. THE EFFECT OF EXTERNAL PRESSURE

Depending on the type of the reinforcing phase and metal liquid, the following variations of the squeeze casting process can be distinguished (Fig. 2):

- squeeze infiltration (compression impregnation, high–pressure infiltration casting) of a porous ceramic preform (fibrous, skeleton, continuous–dispersion, or dispersion) which gives a ready casting, a preshaped product, or a semi–finished composite material) – Figure 2a,
- the fabrication of a casting with local reinforcement (by the porous preform with simultaneous high–pressure infiltration or by an insert – a composite semi–finished product, made as a compound casting, usually of a bimetal type) – Figure 2b,

- the fabrication of a dispersion particulate reinforced casting, where the reinforcing phase is present in the form of particles, whiskers, or short fiber – Figure 2c,
- the fabrication of a hybrid composite casting, reinforced by preform (with simultaneous infiltration), an insert – a composite semi-finished product, and a dispersion phase (sometimes of two types e.g. particles and short fibres, or particles of mixed types, or short fibres) – Figure 2d.

The technology of squeeze casting is also applicable in shaping the liquid–solid composite matrix. Utilizing the rheological properties of a metal suspension, mixed before filling the die and squeezing (the rheocasting process), one can obtain a high–quality composite product, following the rules of a modified compocasting technology. Applying the variable in time pressure values, the casting technologies disclosed in Table 2 can be combined in one organic whole: starting with squeeze casting under vacuum, through compression impregnation (low–pressure infiltration) up to high–squeeze infiltration combined with solidification under pressure of the matrix metal. From the "*historical*" point of view, the term "squeeze casting" denotes "solidification (crystallization) under pressure". The effect of pressure on the process of structure formation in monolithic castings is of a double nature. As an independent thermodynamic factor, the pressure exerts its effect on the basic parameters of the metal solidification process, changing in a direct way a number of its typical features. On the other hand, playing the role of a force factor, the pressure affects in an indirect manner the process of crystallization through an intensification of the heat transfer in a casting–die system. To examine carefully the effective action of pressure in each of the above mentioned cases is very important for the right choice of a methodology adopted in order to control these processes in the specific technologies. As an independent intensive quantity, the pressure is an important measure of the energy state of each material [43]:

$$\Delta G = SdT + Vdp \tag{1}$$

where: ΔG – increase in thermodynamic potential,
S – entropy,
V – system volume,
T, p – system temperature and pressure, respectively,

and as such it effects the energy level of the solidification process, the melting point of not only the matrix but also of the composite [55], the surface tension [50–51], the specific volume [52], the diffusivity [59–61], the radius of nucleus [62–63], and the rate of undercooling [64–67]. The effect of pressure during crystallization reduces the energy of phase interaction at the liquid metal–crystal phase boundary, reducing the value of a critical radius of the nucleus which, in turn, increases the number of the nuclei of crystallization. An important and useful observation is the high probability of an occurrence of the wettability (inherently related with the surface tension) between different phases, appearing under the effect of external pressure even in those situations when under the normal conditions of gravity it would have not appeared [43]. To better illustrate the role of pressure in the process of solidification, Figures 4 and 5 show:

- relative variations in the pressure–affected melting temperature of metals in relation to some selected parameters of the crystal lattice (Fig. 3) for pure metals and alloys (Fig. 4), and
- a relationship between surface tension, increase in melting temperature and isothermal compressibility (Fig. 5).

The effect of pressure changes the density of free electrons, transforms the spectrum of not only electrons but also photons, changes the atomic radius and other characteristic parameters [62]. The non–typical course of the diffusion–related processes which occur during a transformation from the liquid into solid state, the changes in solubility, the effect on the conditions of stabilization of the already existing phases and on the formation of the new ones, the changes in temperature field related with the presence of these phenomena bring about some important variations in phase equilibrium diagrams (Figs. 6 and 7). The phenomenon always accompanying the solidification of metal under pressure, especially in dies, is the high cooling rate. Applying the method of an X–ray structural analysis and the computed phase equilibrium diagrams (temperature–pressure–concentration), the effect of cooling (1 – – 20° C/s) and pressure (0.1 – 400 MPa) on variations in the content of alloying additions in binary aluminium alloys subjected to squeeze casting was examined [69]. It has been assumed that the variations are a result of the combined effect of pressure and of accompanying increased rate of cooling (Fig. 8). The conclusion following these examinations is one: the examined parameters may produce quite different effects: combined, contrasting, predominant, or neutral.

The final effect of the influence of external pressure on the parameters of crystallization and solidification are structural variations. Presenting the structure as a large, complex and hierarchical system [70–72], the structural variations at each of the levels can be elaborated in a consistent way (Table 3). Apart from the expected mechanism of variations, in the last column of the table some other, beside the pressure, means of action applicable in, e.g., modified variants of the squeeze casting, have been mentioned. These, so significant, structural changes generate, in turn, changes in the physico–chemical properties of metals and their alloys. Taking into consideration the complex effect of pressure on various characteristics, an original procedure can be proposed. It consists in introducing the squeeze efficiency factor E_{sq} and in determining its efffect on the n number of characteristics following the equation:

$$\mathrm{E}_{sq}=\frac{1}{2}\sin\frac{360}{n}\left\{\left[\sum_{i=1}^{n}\left(\varepsilon_{\Delta P_i}+1\right)\left(\varepsilon_{\Delta P_{i+1}}+1\right)\right]+\left[\left(\varepsilon_{\Delta P_n}+1\right)\left(\varepsilon_{\Delta P_1}+1\right)\right]-n\right\} \quad (2)$$

where: $\varepsilon_{\Delta P_i}$ – the reduced increase in properties for a given population of the i number of alloys,

$$\varepsilon_{\Delta P_i} = \frac{\Delta P_i - \Delta P_{min}}{\Delta P_{max} - \Delta P_{min}} \tag{3}$$

where: ΔP_{max}, ΔP_{min}, ΔP_i – the percent (relative) increase in the examined properties P (maximum, minimum, intermediate) in the assumed population of alloys.

The studies made for the five (n = 5) examined properties are shown in Figure 9; the shaded area is a graphical presentation of the squeeze efficiency factor E_{sq}. Taking into consideration the properties, like: tensile strength, unit elongation, Brinell hardness, unnotched impact resistance and corrosion resistance, a few tens of the aluminium alloys gravity die cast and squeeze cast under a pressure of 120 MPa applied for the time of 30 s were examined (the 95 mm high cast cylinder of ϕ 65 mm) [43] (Figs. 10 and 11). A generalization of this relationship for the examined population of alloys has given them the following rank in the squeeze efficiency sequence (Fig. 12). Like some Al–Si alloys, the high–strength Al–Cu, Al–Zn–Mg, Al–Cu–Mg, and Al–Zn–Mg–Cu alloys are characterized by the greatest adaptability in the range of the changing squeeze efficiency factor values. This adaptabillity seems to particularly predispose these alloys to an effective application in the squeeze casting process. The alloys assigned for squeeze casting, solidifying in a wide range of temperatures, are characterized by the presence of extensive semi–solid and semi–liquid zones, in other words, the metal matrix is a capillary–porous body of an enlarged range of existence. The effect of external pressure makes the liquid phase get squeezed into the closed regions of shrinkage cavities, which in the gravity castings are usually left unfed with metal due to the presence of non–deformed crystal "*bridges*". On squeezing, the channels are often unblocked or the "*baffles*" inside them are destroyed, which improves to a considerable extent the efficiency of the infiltration feeding of metal.

The general effect of external pressure is that of promoting an increase in the physico–mechanical characteristics of metals and alloys to the level comparable with the values obtained in wrought materials [63] (Table 4). Another advantage of the squeeze casting technology is the additional effect of the reinforcing phase. The composites fabricated by the squeeze casting process are characterized by a shorter time of solidification, and hence by the reinforcing phase/liquid metal reaction time reduced to minimum. The correctly designed and performed technological process is expected to contribute a lot to the mechanism of formation of complex properties in both the matrix and reinforcing phase and to promote interaction between the composite components.

HIGH–PRESSURE INFILTRATION (SQUEEZE INFILTRATION)

In high–pressure infiltration, the liquid metal is acting on the ceramic preforms made of continuous fibres (the fibrous preform), whiskers, short fibres (the skeleton preform), particles (the dispersion preform or the, so–called, bed of particles), or of the mixed types of reinforcement combined together (the hybrid preform).

The difference in pressure required for correct infiltration of porous preform can be expressed by the following formula [76–78]:

$$\Delta p \geq p_{ep} - p_{cp} = \Delta p_{\gamma} - \Delta p_{\eta} \tag{4}$$

where: p_{ep} – the external pressure of metal liquid exerted onto the die surface,

p_{cp} – the pressure of gas enclosed inside the preform,

Δp_{γ} – the difference in metal pressure at the metal liquid front, (the, so–called, Gibbs–Thomson pressure),

Δp_{η} – the difference in pressure caused by the metal liquid flow through a porous preform (the resistance of flow).

On the other hand, the metal liquid should be subjected to the following difference in pressure (the simple arrangement of parallel fibres):

$$\Delta p \geq \frac{\sigma}{r_w\left[\left(\frac{\pi}{4V_w}\right)^{0.5} - 1\right]} \tag{5}$$

where: σ – the surface tension of metal liquid on the preform fibre (in the reinforcing phase),

r_w – the (reduced) radius of reinforcing fibre,

V_w – the volume fraction of reinforcing fibre.

From the above given equations it follows that the conditions of infiltration depend on the contact angle, given in a non–explicit form (in Δp_{γ}, Δp_{η}, and σ) on the porosity and geometry of a preform (r_w, V_w, Δp_{η}), on the gas counter in a die (p_{cp}) and, finally, on the most important factor which is the exerted external pressure (p_{ep}). The theoretical computations give the values reduced in respect to those required in practical applications. The main reasons of the required increase in infiltration pressure are the insufficient ventility parameters of preforms before the front of infiltration *2* (Fig. 13) and failure in observing the temperature–related parameters of the process, resulting in, e.g., an excessive growth of the boundary layer of the metal solidifying under gravity, otherwise called solidification front *4*, and in an additional sealing of the preform – die system – surface *3* in Figure 13.

In Table 5 some selected physico–mechanical characteristics of "reinforcement" used most frequently for the preforms are given (Figs. 14 and 15). The successive drawings show the preforms: fibrous (Fig. 16) and skeleton (Fig. 17), together with an example of its potential application for automotive parts (Figs. 18, 19 and 20).

In the case of carbon and graphite fibers used for continuous reinforcement, along with these fibers also some technological and barrier coatings are applied. Aluminium is wetting graphite at a temperature above 1000° C, but the rapidly forming aluminium carbide Al_4C_3 makes the application of so high temperatures quite impossible. The formation of Al_4C_3 takes place at temperatures lower even than 1000° C; the resulting product assumes the shape of either a continuous film or of the lamellae deposited in the surface of fibers. In the latter case the effect of pitting occurs [80], and it reduces considerably the composite strength behaviour, resulting from the law of mixing. Hence, the necessity of applying coatings which play the double role acting as a layer increasing the wettability and preserving the occurrence of fiber–die system. The materials used for coatings are nickel, silver, copper, tantalum, boron, silicon, titanium carbide, and zircon [82–85]. Other promising materials for coatings are sodium, tin and magnesium [86]. Yet, the main drawback of these coatings is the fact that they are not air stable. Therefore, at the AEROSPACE CORPORATION a new technology providing the use of precursor wire has been developed. The precursor wire is a set of graphite fibers coated and immediately infiltrated during the process. The precursor wire is next hot press moulded into arbitrary shapes [87–90].

Table 6 shows in a concise form the mechanical behaviour of composites reinforced with continuous fibers, short fibers, whiskers and particles, fabricated mainly by the squeeze casting process as well as by compocasting, rheocasting and gravity casting. The designation PRC (pressure casting) was left, although from the description it follows that all those cases referred to the squeeze casting process. The strength and stiffness of the cast composites reinforced with continuous fibers of random distribution are a direct function of the content of reinforcing phase (Fig. 21). In the case of an assumed random distribution there is a limit content of the reinforcing phase for which the examined characteristics reach a maximum value [75] (Fig. 22). The fatigue strength of composites measured by the number of cycles, also increases with an increase in the fiber content (Table 7); sometimes with the threshold value exceeded, it reaches the asymptotically constant values (Fig. 23). A relatively simple method of fabrication of composites reinforced with carbon or graphite fibers consists in placing a fibrous preform (cut out from the carbon or graphite felt) in the cavity of a die (Fig. 24) and in subjecting it to high–pressure (230 MPa) infiltration with lead for the time of 30 s (including the solidification of metal under pressure). Before infiltration the carbon felt was preheated at a temperature of 400° C for the time of 2 minutes. Basing on the results of structural examinations of a fracture of carbon felt–lead composite, a low fiber concentration, consistent with the squeeze casting direction, was observed. The metal matrix was free from any structural discontinuities.

Under the conditions of normal pressure the Pb–C system is non–reactive and non–wetting [113], and therefore, due to pressure activation, during the high–pressure infiltration the interaction between the carbon fibers and liquid Pb becomes much stronger [114, 115]. An additional favourable effect of external pressure is the formation of fine–grained metal structure inside the carbon felt.

The results of mechanical testing compiled in Table 8 are as follows:

- the reinforcement of the lead matrix with a common carbon felt brings about an increase in the tensile strength and hardness,
- squeezing slightly improves the tensile strength and hardness,
- the reinforcement with carbon felt improves the proof stress ($R_{0.02}$; $R_{0.05}$; $R_{0.1}$; $R_{0.2}$) the accommodation limit (R_a), and the approximate fatigue limit for rotary bending (Zg_0),
- the modulus of elasticity changes for the successive blocks of cycles and its value for lower stresses is usually lower than the value of the modulus for blocks characterized by a higher lower limit value of stresses. For every ratio there is an area of the stresses with a relatively stable value of the modulus; it assumes the value of about 13000 MPa for lead gravity cast, 14000 MPa for lead squeeze cast, and about 17000 MPa for the composite.

A schematic model of the process of failure in the examined composite with a ductile matrix in the non-reactive system has been based on hypotheses and observations (Fig. 25) [116].

The model causing a failure included the following elements: bending, cracking, sliding and sagging of the reinforcing fiber matrix. It can be observed that the length of a fiber sticking out from the surface of a fabric depends on its inclination to the crack orientation (Fig. 25).

For the local reinforcement of pistons of I.C. engines, the preforms made of short Al_2O_3 fibres of a porosity reaching 80% of the structure (Fig. 26 is showing structure before infiltration, and Figs. 27 and 28 – after infiltration) are used. Before placing it in the die cavity for squeezing, the preform is preheated to a temperature of 600–700°C and owing to the high thermal capacity of the Al_2O_3 fibres it preserves the high temperature for quite a long time. The technology of squeeze casting enables not only the reinforcement of the shaped piston (Fig.19) with simultaneous inserting under pressure of a cast iron or nickel ring, but also a reinforcement of the entire piston enclosing the combustion chamber to a thickness such that it is possible to make in the impregnated ceramic preform a groove for the first sealing ring (Fig. 20). Due to this design and the use of proper materials it becomes possible to achieve higher values of hardness, stiffness and better fatigue strength of composite pistons, along with a lower coefficient of thermal expansion and improved dimentional stability. The reinforced zones are, moreover, characterized by a better resistance to thermal shocks. Compared with monolithic alloys, the samples of Al alloy/20 vol.% Al_2O_3 and Al/20 vol.% SiC composites fabricated by squeeze casting, reveal a few ten times higher resistance to the formation of cracks, accused by the thermal loads changing in cycles (Fig. 29).

The local reinforcement of castings may assume quite complicated forms. In a number of the designs used so far, in the cylinder blocks of I.C. engines, the cylinder bearing surface is made inside the cast iron sleeves mounted in the cast cylinders not earlier but during shaping of a product in a casting process. The replacement of a bimetal casting with monolithic casting becomes possible due to the application of hypereutectic silumins, whose structure composed of the hard crystals of primary silicon in a soft aluminium matrix ensures that all the requirements imposed onto a piston–cylinder couple operating under the conditions of friction shall be duly satisfied. The next step towards an improvement in quality was the application of a silicon carbide–nickel film onto the cylinder bearing surface made of an aluminium alloy (Fig. 30). In this case an optimum solution has proved to be the use of ceramic preforms, having as a matrix the short fibers of Al_2O_3, with the silicon grains of an appropriate size and shape inserted between these fibers. The satisfactory thickness of these preforms after high pressure infiltration is 2 mm, and the high physical and mechanical characteristics make it possible to reduce the distance between the adjacent bearing surfaces to 5.5 mm. Compared with the values of 3 and 8 mm in cast iron cylinder sleeves (e.g. in the case of a 10–cylinder engine), this new solution enables a reduction in the engine weight by even as much as a few kilograms. The second advantage is as follows: because the thermal conductivity of a composite insert is lower than that of a cast iron sleeve, the upper piston rings can be moved closer to the cylinder crown in the combustion chamber. The possibility also arises to change the design of the chamber itself in a way which will enable the engine to run at higher temperatures, saving in this manner the fuel consumption and reducing the heat emissions [117]. On the other hand, the use of composite pistons, reinforced in the zone of the piston crown and with a reduced combustion chamber, creates the opportunity of increasing the compression ratio and the engine power, along with a more complete combustion, which is certainly very important from the ecological point of view and gives additional argument for a more extensive use of the composite materials in heavy duty I.C. engines.

One of the specific designs and engineering solutions of fabricating composite castings by the method of high–pressure infiltration (Fig. 31) consists in increasing the abrasion wear resistance on the surface of the holes in which the pins of a track link base are operating (due to the use of steel pipes placed in the preforms). The ends of the pipes are closed with four plugs. The whole is placed in a lower half die. Before pouring of metal the upper half die is pressed to its lower counterpart, and the liquid metal is poured through a hole in the upper half die. The pressure, causing the preform infiltration and the solidification under pressure of the entire casting, is applied from the top by means of a stamp. The ready casting is ejected from the die by bottom ejectors [118].

SQUEEZE CASTING OF PARTICULATES REINFORCED CAST METAL MATRIX COMPOSITES

The particulates reinforced cast metal matrix composites are gaining a very strong position among the metal matrix composite materials, mainly due to the economic reasons. This is particularly true when a comparison is made with the continuously reinforced metal matrix composites [119–122]. Owing to their availability, the relatively low cost of fabrication, and the flexibility of processing, aluminium is nowadays the most popular matrix material used in composites included into this group. Magnesium, in turn, characterized by a similar set of the physical and mechanical characteristics may find its way to application in ultralight CMMCs. Titanium may give much better strength characteristics but its higher melting point and the strong chemical affinity to ceramic materials may cause some serious technological problems. Due to the low value of the modulus of elasticity of Al and Mg (and of their alloys) the relatively low combined with an average mechanical strength, the effect of reinforcement is obtained with but only very small content of the particulates, which enables the composites to preserve their low density, similar to the density of the matrix. In the case of titanium which has a higher value of the modulus of elasticity and of the strength, it is much more difficult to achieve the effect of reinforcement using particulates. Therefore, used as a matrix material, titanium seems to be better reinforced by the continuous fibres and whiskers.

At the very beginning, the material used most frequently for the particulates reinforced composites were the relatively cheap particles of SiC and Al_2O_3 (Table 9) of dimensions 10–20 μm [123]. The possibilities of using ZrO_2 [124, 125], SiO_2 [126], B_4C [127–128], or TiO_2 [125] (Table 10) were also investigated. In comparison with the unreinforced alloys, one of the important sectors of the composites application results from the fact that the composites acquire and preserve appropriate tribological characteristics [128], erosion and abrasion resistance [129 and 130, 131, respectively] as well as the antiseizing performances [132]. For example, the particles of mica and graphite are lighter than aluminium, and during centrifugal casting they are collected on the internal surface of the cast bearing, conferring to this bearing the self–lubricating properties. Such bearings are a few times lighter than the products made of lead or antimony bronzes, though their properties are comparable [133–138]. The resistance to erosion and abrasion is a good example of the symbiosis existing between various components of a composite. The hard ceramic phase protects the soft and more ductile matrix which, in turn, dissipates better the heat and impact energy.

The casting methods of fabricating the particulates reinforced metal matrix composites are mainly based on mixing; they are also called the vortex process. In squeeze casting, obtaining of a homogeneous suspension of the particles of a reinforcing phase in the metal matrix before the application of pressure is of great importance, since the external pressure makes the composite behaviour stable, due to a higher solidification rate, and the favourable effect of pressure onto the distribution of the reinforcing phase of particulates can be levelled down. Mixing of suspension for certain period of time may have an unfavourable effect on the reactivity of a matrix–reinforcement system. For example, SiC is thermodynamically unstable in majority of the silicon–free aluminium alloys, and it forms aluminium carbide following the reaction:

$$4\,Al + 3SiC \rightleftharpoons Al_4C_3 + 3Si \tag{6}$$

To prevent the formation of the brittle and corrosion–promoting aluminium carbides, an appropriate amount of silicon is introduced to the alloy matrix (Fig. 32) [139]. Other carbides, like B_4C or TiC are also unstable, but they often react in a much more complex way [140]. Magnesium does not form stable carbides but ceramic carbides are stable in molten magnesium. Unfortunately, most of magnesium alloys contain aluminium and other additives which can form carbides during prolonged time of contact. The alumina Al_2O_3 is stable in liquid aluminium but in the Al–Mg systems it reacts with magnesium following the reactions:

$$3Mg + Al_2O_3 \rightleftarrows 3MgO + 2Al \tag{7}$$

$$3Mg + 4Al_2O_3 \rightleftarrows 3MgAl_2O_4 + 2Al \tag{8}$$

The equilibrium contents of magnesium, calculated from the above given formula, confirm the fact that, contrary to SiC which is stable below the solidus line, alumina may also react in the solid state forming the crystals of $MgAl_2O_4$ spinels [141] (Fig. 33).

The, described in literature, laboratory and semi–technical methods of fabrication of the particulates reinforced composites comprise the following stages:

I) – the operation of particulates preparation (application of barrier or technological coatings, thermal activation, e.g. roasting (heating) of SiC at a temperature of 700°C for 1 hour),

II) – mixing of the composite components to obtain a homogeneous suspension in special vessels ensuring the mixing rate n = 200–500 rev/min for a time of e.g. 30 – 60 minutes at a temperature close to or lower than the liquidus point of the metal matrix,

III) – casting in the processes of squeeze casting, compocasting, continuous casting or gravity casting,

IV) – possibly also further processing of the fabricated semi–products by means of casting or plastic working.

A patent used by DURAL ALUMINIUM COMPOSITES CORPORATION [142] provides for initial degassing of molten matrix metal adding the preheated particulates of the reinforcing phase (which, as one can suppose, is done mainly for the removal of moisture prior to dispersion), and vigorous mixing in an evacuated mixing vessel to eliminate closed gas cavities in the fabricated composites. A peculiarity of this method is the use of a mixing vessel of special design (Fig. 34). The formation of a specific type of the vortex, which makes sucking in of the residues of an active gas and oxides from the metal surface into the metal liquid impossible or – speaking more strictly – difficult, should be avoided. The method described in the patent has successfully been used for various ceramic particulates and has proved to be most useful in the case of SiC added to Al–Si alloys (silicon in aluminium for preventing the chemical reaction during prolonged mixing) and in the Al_2O_3 particulates – reinforced aluminium alloy composites with various matrices. The DURALCAN Company (DIVISION OF ALCAN ALUMINIUM CORPORATION, San Diego, California, USA) makes semi–finished products for further recycling, ingots for extrusion and rolling, slabs and pigs. In products subjected to plastic working the reinforcing phase is Al_2O_3, in cast materials – SiC (Table 11).

For the cast composites Duralcan recommends a modified process of melting, casting and recycling (Fig. 35). The composites for further recycling are also fabricated by other companies, like: COMRAL, PECHINEY, MARTIN MARIETTA, COMALCO, DWA, BRITISH PETROLEUM, COSPRAY, etc. In comparison with the plain unreinforced matrix, composites are characterized by a much better wear resistance, fatigue strength, thermal conductivity altered to quite a considerable degree, and reduced coefficient of thermal expansion (Tables 12 and 13).

In the technical reference literature there is practically no complex description of the structure and properties of the squeeze cast particulates reinforced MMCs, although the whole group of composites made by Duralcan has been assigned for use in the squeeze casting process (according to a description given by the manufacturer – for pressure die casting). The advertized casting made by the squeeze casting technology is a chain for motor–cycle, cast in a F3D20S composite (Fig. 36). The stand for squeeze casting of composites (particulates reinforced), installed at the FOUNDRY RESEARCH INSTITUTE in Kraków comprises a resistance furnace, on which a device for mixing of liquid metal under the atmosphere of an inert gas has been mounted, and a hydraulic press which can operate in semi–automatic cycle (Fig. 37). The device for mixing of liquid metal performs a double function. On the one hand, it serves for introducing the particles of a reinforcing phase in the stream of preheated argon directly to the surface of a vortex formed by the mixing arm of a special design, and provides intensive mixing of the suspenion to distribute the particles in a uniform way within the entire volume of a crucible (Figs. 38 and 39). On the other hand, the device may be used to maintain a homogeneous distribution of the ceramic particles in a metal bath during remelting of cast composites fabricated by other technologies (Figs. 40 and 41). During the performance of each of the above quoted main operational systems, an inert gas (argon, nitrogen) is fed to the surface of metal liquid, which affects to a significant extent the surface quality of molten composite (Fig. 42), reducing the content of oxides. Immediately after completing the operation of mixing or during this operation (Fig. 43), the liquid composite is transferred to the cavity of a die, placed on the table of a hydraulic press (Fig. 44) where the solidification under pressure is effectuated. When pistons for I.C. engines are fabricated by the squeeze casting process (Fig. 45), the successive stages of the process are comprised in the following operations:

1) application of protective and separating coatings onto the working surfaces of a die, i.e. onto the squeeze element and die cavity (Fig. 46); the die is preheated, and the coating is applied by a spray gun (water mist in the jet of compressed air);

2) filling of the die cavity with liquid composite to a level of the casting volume (Fig. 47);

3) locking of the die parallel with the application of pressure in a range of several tens of MPa, indispensable for full solidification of the casting (Fig. 48); because during the pressure casting the processes of heat transfer are proceeding at a much higher

rates, when the die temperature exceeds a pre–established value, the die is cooled with water or air;

4) opening of the die along with setting the ejectors system in motion (Fig. 49);

5) ejecting the ready composite casting by means of a manipulator or – in prototype production – by hand (Fig. 50).

Figure 51 shows composite pistons fabricated by the squeeze casting process.

The external pressure favours not only a uniform distribution of the reinforcing particles, like SiC (Fig. 52), mixed oxides of Al_2O_3+SiO_2 in the spherical form (COMRAL – Fig. 53), cenosphere (Fig. 54), and changes the metal solidification process inside the reinforcing particles of the type of flyashes (Fig. 55), ensuring fast bonding at the aluminium alloy – SiC phase boundary (Fig. 56), but it also promotes in a significant way the structure refining in composites reinforced with short or long fiber ceramic preforms (Fig. 57).

SQUEEZE CASTING OF HYBRID COMPOSITES

From among the very scarce reference literature items devoted to this problem, one can mention [145] where the possibilities of making hybrids composites of the type: Al–SiC (fibers) + SiC (particles) have been investigated (Table 4). The possibility to control the level of properties through changes in the ratio of the reinforcing phases content has been mentioned. The high level of temperatures used in the process is very important; specially critical is the temperature of the die for squeeze casting as it considerably affects the process of high–pressure infiltration and the time of solidification of the metal matrix under the effect of pressure during squeeze casting. It may contribute to an excessively strong interaction between the matrix components, which has a destructive influence on the attainable level of properties.

APPLICATION. ECONOMIC ASPECTS

The cast metal matrix composites are gaining an always more stable position beside the commonly used materials. A marketing analysis of the development tendencies of CMMCs reveals a definite increase in their application; the quantity of the used products is shifting from the field of military and space technology applications to the civil engineering area [1].

The so far known applications of cast composite, mainly in the automotive industry, are illustrated in Table 15 [13].

At present, a tendency to shift the fabrication of composites from the specialized plants to those making the ready semi–finished products is observed. This commercialization of the centralized production is of great practical importance because the manufacturers of final products get the ready technology of recycling and the most important guidelines for design and technology. The fact that the technological processes of making composite castings by means of the liquid phase reinforcement methods have already been mastered by over 100 American foundries, obtaining the high level of properties and an increasing rentability of the fabrication process provides a firm basis for forecasting a rapid growth in the production rate and application of CMMCs. The so far used prices of materials applied in the production of composites are given in Table 16 [144]. If these favourable trends in the world foundry practice related with a quick progress in the world communication system are maintained, a notable drop in prices of the composite products can be expected. The parallel progress in the techniques of machining, joining of materials, and utilization of wastes also promotes a wider use of CMMCs.

A comparison of the prices of aluminium–based composites obtained by various methods of fabrication, related to 1 kg (Fig. 58), leads to a conclusion that among various processes of fabrication (like powder metallurgy, stream deposition of particles, or high–pressure infiltration in autoclave), squeeze casting is the most attractive, most promising and competitive method. Therefore, combining in itself an optimum level of the designing and engineering potentials (near net shape castings) with the high level of attainable properties and economic indices, this technology is now becoming the most versatile tool of fabrication of CMMCs, especially those based on aluminium.

Figure 59 is a symbolic illustration of the material–design–economic flexibility of squeeze casting technology applied in fabrication of composite elements and referred to both the matrix material (the possibility of using alloys for plastic working, the favourable effect of pressure on the structure and properties) and reinforcing phase (the uniform distribution of a reinforcing phase, bonding). The figure also illustrates a relative, compared to autoclaves, simplicity of the equipment and facilities used even in the case of intricate castings as well as the possibility of automatization, including full process control, and relatively low production costs.

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Zbigniew Górny, Jerzy Sobczak

KOMPOZYTY METALOWE WYTWARZANE METODĄ PRASOWANIA W STANIE CIEKŁYM

Streszczenie

W artykule rozpatrzono teoretyczne i praktyczne aspekty zastosowania ciśnienia zewnętrznego do uzyskiwania metalowych materiałów kompozytowych zwłaszcza w odniesieniu do sposobu squeeze casting. W zależności od rodzaju cieczy metalowej i postaci fazy zbrojącej zaproponowano szereg schematów procesu krzepnięcia pod ciśnieniem, ilustrując każdy z nich danymi o właściwościach, strukturze i specyfice otrzymywania. Zaprezentowano szereg własnych rozwiązań konstrukcyjno-technologicznych, stosowanych w Instytucie Odlewnictwa w Krakowie do wytwarzania w skali laboratoryjnej i półtechnicznej materiałów kompozytowych o osnowie stopów metali nieżelaznych. Rozpatrzono możliwe obszary zastosowania i aspekty ekonomiczne metalowych materiałów kompozytowych. Proponowana publikacja jest pierwszą w kraju próbą kompleksowego ujęcia zastosowania procesu prasowania w stanie ciekłym w odniesieniu do nowej grupy materiałów kompozytowych.

Zbigniew Górny, Jerzy Sobczak

DIE KOMPOSITEN MIT DEM METALLISCHEN GRUNDGEFÜGE NACH DEM SOGENANNTEN "SQUEEZE CASTING PROCESS" (PRESSGIESSEN VORGANG) HERGESTELLT

Zusammenfassung

In der vorliegenden Arbeit wurden die theoretischen und praktischen Probleme betrachtet, welche mit Anwendung des Aussendrucks verbunden sind, und zwar um die metallischen Kompositmaterialen zu erhalten, besonders den "squeeze casting" - Vorgang betreffend. Von der Art des flüssigen Metalls, wie auch von der Form der Armierungsphase abhänging hat man eine ganze Reihe von Schemen des Erstarrungsvorganges unter Druck vorgeschlagen, wobei jedes mit Angaben über die Eigenschaften, über Gefüge und spezifische Herstallungsverfahren ergänzt wurde. Man hat auch einige eigenen konstruktiv-technologischen Lösungen besprochen, welche im Giessereiinstitut in Kraków zur Herstellung von Kompositmaterialien mit dem Grundgefüge von leichtmetallischen Legierungen im Labor- und halbtechnischen Ausmassę angewendet werden. Die möglichen Anwendungsgebiete der Kompositmaterialien und die damit verbundenen ökonomischen Probleme wurden erwogen. Die beabsichtigte Veröffentlichung beschreibt einen Versuch, zum ersten Male im Lande vorgenommen, die Anwendung von Pressverfahren im flüssigen Zustande bezüglich einer neuen Gruppe von Konstruktionsmaterialien vollständing zu erfassen.

Zbigniew Górny, Jerzy Sobczak

LES COMPOSITES Á LA MATRICE METALLIQUE FABRIQUÉS PAR UN PROCÉDÉ DE PRESSAGE A L'ÉTAT LIQUIDE

Resumé

Dans le mémoire ci-dessous on a considéré des aspects theoretiques et pratiques de l'emploi de la pression extérieure pour obtenir des composites à la matrice métallique surtout lorsqu'il s'agit du procédé dit "squeeze casting" (coulée sur pressage à l'état liquide). En égard au type du liquide métallique et à la forme de la phase d'armature on a proposé quelques schèmes du processus de solidification sous pression, chaque d'eux étant illustré par des données ayant rapport aux propriétés, à la structure et aux procédés specifiques afin d'obtenir des composites. On a présenté un ensemble des solutions particulières de construction de technologie employées à l'Institut de la Fonderie à Cracovie pour produire à l'échelle de laboratoire et semi-technique, des composites à la matrice consistant des alliages des métaux non-ferreux. On a considéré des domaines possibles d'emploi et des aspects économiques des composites à la matrice métallique. La publication proposée presente, pour la premiére fois au pays, un essai de l'étude complète de l'emploi du procédé de pression en état liquide au nouvel ensemble des matières à l'usage pour la construction.

TABLES
AND
FIGURES

Table 1:

Synthesis of cast metal matrix composites

Period	Location	Composite system	Technique used
1965	Inco, USA	Al+GR1)	Particle coating and gas injection
1968	IITK, India	$Al+Al_2O_3$	Mg inoculation and stir–casting (mixing)
1974	ITSc, India	Al+SiC; Al+mica	Mg inoculation and stir–casting
1975	MIT, USA	$Al+Al_2O_3$	Mg inoculation and compocasting
1978	Hitachi, Japan	Al+GR	Squeeze casting (pressure casting)
1979	RRL, India	$Al+TiO_2$, $Al+ZrO_2$, Al+flyash	Mg inoculation and stir–casting
1983	Martin Marietta, USA	Al+TiC	XD process
1983	Dupont–Toyota, USA/Japan	$Al+Al_2O_3$	Squeeze casting (squeeze infiltration)
1984	RRL, India	Al+microballoons	Stir casting
1984	Norsk.Hydro, Norway	Al+SiC	Stir casting
1985	Iraq	Al+MgO–coated Al_2O_3	Stir casting
1986	MIT, USA	Al+SiC	Pressure infiltration
1986	DURAL, USA (Duralcan)	Al+SiC; $Al+Al_2O_3$	Stir casting under reduced pressure
1987	Martin Marietta, USA	TiAl, $Ti_3Al+TiB_2$, $NiAl+TiB_2$	XD process
1987	MIT, USA	Fe+TiC	In situ synthesis
1987	Comalco, Australia	Al+coated Al_20_3	Stir casting
1988	Lanxide Corporation, USA	$Al+Al_2O_3$, Al+SiC	Pressureless infiltration (quasi–gravity in nitrogen)
1988	Grenoble, France	Al+SiC	Stir casting
1988	Drexel Univ., USA	Al+TiC	In situ synthesis
1989	University of Wisconsin Milwaukee, USA	Cu+GR	Stir casting and compocasting
1989	Honda, Japan	$Al+Al_2O_3+C$	Squeeze casting
1) GR – graphite			

Table 2:

Classification of the casting processes of obtaining cast metal matrix composites with application of external pressure [43]

Method of casting	Causative agent	Approximate pressure values	Source (reference)
Vacuum infiltration, pressureless infiltration	gas	$p<0.1$ MPa	[38]
Vacuum infiltration with counter–pressure		$p<1$ MPa	[39]
Autoclave, compression impregnation		$p\leq 10$ MPa	[40]
Low pressure, gas pressure infiltration		$p\leq 15$ MPa	[41, 42]
Pressure die casting	solid body	50–70 MPa	[43]
Compocasting		50–70 MPa	[44]
Squeeze casting (high pressure infiltration casting)		50–200 MPa	[45, 46, 47]
Casting (crystallization) under electromagnetic pressure	electromagnetic field	–	[48]
Centrifugal casting (spinning of moulds after pouring)	centrifugal force	–	[41]

Table 5:

Typical properties of selected reinforcements[1]

Property	Al_2O_3 (Saffil)	Al_2O_3 (Spinel)	Al_2O_3 (FP)	SiCw	SiC (Nicalon)	Fiberfrax	Celion (PAN)	Thornel P55
Crystal structure	δ	Spinel	α	β	β	Amorphous		
Density (g/cc)	3.30	3.2–3.25	3.9	3.19	2.55	2.73	1.76	1.8
Diameter (µm)	3–4	17.00	20±5	0.1–1.0	10–20	2–3	7	10
Length (µm)	500 (discontinuous)	Continuous (1000 filaments/tow)	Continuous	30–100	Continuous (500 filaments/tow)	Discontinuous	Continuous (6000 filaments/tow)	Continuous (2000 filaments/tow)
Thermal expansion coefficient ($10^{-6}K^{-1}$)	–	–	7.4	4.8	3.1		–1.7	–1.3
Tensile strength (MPa)	>2000	1800	1380–2070	3000– –14000	2480–3240	1600	2758	2100
Young's modulus (GPa)	300	210–250	380	400–700	179–207	104	234	379
Elongation (%)	0.67		0.4	1.23	1.5		1.2	0.5
Composition	96% Al_2O_3 4% SiO_2	85% Al_2O_3 15% SiO_2	>99% Al_2O_3 (–005 µm SiO_2 coating)	>98% SiC	61% SiC 28% SiO_2 10% C	48% Al_2O_3 52% SiO_2		

[1] Data are primarily taken from manufacturers' product literature.

Table 6:

Comprehensive summary of mechanical properties of cast composites

Matrix	Fiber	V_f	Fabrication method[1]	Fabrication conditions				Mechanical properties			Elongation[8] (%)	Source (ref.)	Remarks
				Preform temp.[2] (K)	Pouring temp.[3] (K)	Press[4] (MPa)	Time (s)	YS[5] (MPa)	UTS[6] (MPa)	E[7] (GPa)			
1	2	3	4	5	6	7	8	9	10	11	12	13	14
c.p. Al	Al_2O_3 (Saffil)	0.0	SQC[9]	495	1025	80	120	28	40	68	37[10]	[91]	As cast
		0.20	SQC[9]	875	1025	80	120	75	142	83	1.1[10]	[91]	As cast
c.p. Al	Al_2O_3 (Spinel)	0.50	SQC	770– –1020	900– –1200	50	<60		860	150		[92]	As cast
Al (99.9%)	SiC_w (Preform)	0.0	PRC[11]	825	1075	92	180	127	225		4	[93]	
		0.20	PRC	825	1075	90	180	207	260		4	[93]	
		0.23	PRC	825	1075	92	180	190	250		4	[93]	
		0.28	PRC	825	1075	92	180	200	270		3.5	[93]	
		0.32	PRC	825	1075	92	180	260	312		2.8	[93]	
		0.40	PRC	825	1075	92	180	340	390		0.8	[93]	

Table 6 (cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Al+10Si	SiC (Nicalon)	0.0	SQC	825	$L^{12)}$+160	50			257			[94]	
		0.45	SQC	825	L+160	50			430	95		[94]	
Al+12.5Si	Al_2O_3 (Saffil)	0.0	SQC	775	1125	50	40		105			[95]	
		0.06	SQC	775	1125	50	40		153			[95]	
		0.12	SQC	775	1125	50	40		180			[95]	
		0.19	SQC	775	1125	50	40		217			[95]	
A356 (Al+7Si+ +0.3Mg+0.3Fe)	Carbon (M40)	0.35	SQC	723	1055				1025	171		[96]	As cast
		0.35	SQC	823	1055				796	160		[96]	As cast
		0.35	SQC	873	1055				855	165		[96]	As cast
		0.35	SQC	923	1055				902	152		[96]	As cast
		0.35	SQC	873	1055				745	218		[96]	As cast Aged: 473K/h
A356 (Al+7.1Si+ +0.34Mg)	SiC_p	0.0	CAST					127				[97]	As cast
		0.0	CAST					240				[97]	Aged: 430K/16h
Al+7Si+ +0.65Mg	SiC_p	0.15	CAST					200				[97]	As cast
		0.15	CAST					335				[97]	Aged: 430K/16h
Al+7Si+0.6Mg	SiC (Nicalon)	0.00	$CC^{13)}$/SQC					130	330		$1.9^{10)}$	[98]	T6
		0.08	CC/SQC					130	285		$0.5^{10)}$	[98]	T6
		0.15	CC/SQC					130	210		$0.4^{10)}$	[98]	T6
	SiC_w	0.08	CC/SQC					120	240		$0.6^{0)}$	[98]	T6
Al+12Si+ +2.3Cu+1.2Fe+ +1Mg+1Ni+1Zn	Al_2O_3+ +SiO_2 (Fiberfrax preform)	0.00	SQC					173	221			[99]	Aged: 533K/100h
		0.18	SQC					228	250			[99]	
		0.23	SQC						223			[99]	
Al+4Cu	SiC (Nicalon)	0.35	SQC			50–200			450		0.4	[100]	
Al+4.5Cu	SiC (Nicalon)	0.00	SQC	525	960	140	60–90	107	182	71	17	[101]	Chopped fibers
		0.06	SQC	525	960	140	60–90	153	192	78	5.1	[101]	
		0.10	SQC	525	960	140	60–90	184	198	82	3.5	[101]	Vortex mixing
Al+5Cu	Al_2O_3 (Spinel)	0.50	SQC	770–1020	900–1200	50	<60		590	150		[92]	As cast

Table 6 (cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
		0.50	SQC	770– –1020	900– –1200	50	<60		600			[92]	723K/ /1000h
		0.50	SQC	770– –1020	900– –1200	50	<60		530			[92]	823K/ /1000h
		0.50	SQC	770– –1020	900– –1200	50	<60		430			[92]	873K/ /1000h
		0.50	SQC	770– –1020	900– –1200	50	<60		400			[92]	873K/ /2500h
Al+2Cu+1.2M+ +0.9Ni+1.2Fe	Al_2O_3 (Saffil)	0.00	SQC	495	1025	80	120	388	431	77	2.5[12]	[91]	T6
		0.20	SQC	875	1025	80	120	317	383	102	0.8[12]	[91]	T6
Al+3Cu+3Mg	Al_2O_3 (Saffil)	0.00	SQC					319	345	72	1.2[12]	[102]	
		0.20	SQC					385	401	89	0.8[12]	[102]	
Al+4.5Cu+3Mg	Al_2O_3 (Saffil)	0.00	SQC					344	376	66	1.2[12]	[102]	
		0.20	SQC					371	375	89	0.8[12]	[102]	
Al+3.75Mg	Al_2O_3 (Saffil)	0.10	RHE[14]/ /SQC	525	955	140	90	186	243	76		[103]	Vortex mixing
Al+5Mg	Carbon (M40)	0.35	SQC	875	1055				782	180		[96]	
		0.35	SQC	875	1055				655	230		[96]	623K/1h 453K/2h
Al+3Mg+2Zn	Carbon (M40)	0.35	SQC	875	1055				1110	160		[96]	
		0.35	SQC	875	1055				432	218		[96]	723K/24h 473K/1h
Al+7Mg+2.5Zn	Carbon (M40)	0.35	SQC	875	1055				948	142		[96]	
		0.35	SQC	875	1055				565	230		[96]	683K/1h 523K/1h
Al+1Mg+0.8S+ +0.3Cu+0.2Fe+ +0.15Mn	SiC_p (3 μm)	0.0	CC					91	169		18	[104]	Extruded
		0.0	CC					276	294		7	[104]	T6
		0.05 (by wt)	CC					96	172		13	[104]	Extruded
		0.05 (by wt)	CC					279	308		5	[104]	T6
		0.10 (by wt)	CC					113	164		3	[104]	Extruded
		0.10 (by wt)	CC					277	286		1	[104]	T6
Al+1.5Li	SiC_w (Preform)	0.20	PRC	825	1075	92	180	167	242		2.6	[93]	As cast
		0.20	PRC	825	1075	92	180	185	260		2.1	[93]	T6
Al+2.0Li	SiC_w (Preform)	0.20	PRC	825	1075	92	180	179	255		2.5	[93]	As cast
		0.20	PRC	825	1075	92	180	212	281		1.7	[93]	T6
Al+2.7Li	SiC_w (Preform)	0.20	PRC	825	1075	92	180	194	288		2.1	[93]	As cast
		0.20	PRC	825	1075	92	180	242	315		1.6	[93]	T6
Al+4.0Li	SiC_w (Preform)	0.20	PRC	825	1075	92	180	212	297		0.6	[93]	As cast
		0.20	PRC	825	1075	92	180	260	327		0.4	[93]	T6

Table 6 (cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
2014 Al	SiC_p	0.00	CAST					414		72	10	[105]	Extruded T6
		0.15	CAST					462	473	95	4	[105]	Extruded T6
2024 Al	SiC_w	0.00	SQC						430	70		[106]	
		0.20	SQC						580			[106]	
6061 Al	SiC_p	0.00	CAST					308	326	68	15.1	[105]	Extruded T6
		0.10	CAST					321	351	79	7.5	[105]	Extruded T6
		0.20	CAST					343	377	97	2.8	[105]	Extruded T6
6061 Al	SiC_w	0.00	SQC						320	70		[106]	
		0.20	SQC						500	105		[106]	
6061 Al	SiC_w	0.20	SQC	870–-1070	970–-1140	10–30			500			[106]	
6061 Al	SiC (Nicalon)	0.38	SQC	750–-860	970	25–100			450		2	[100]	
7075 Al	SiC_w	0.00	SQC						530			[106]	
		0.20	SQC						620			[106]	
Pure Mg	Boron	0.00	Infiltration						172	45		[108]	
		0.70	Infiltration						1055	276		[108]	
c.p. Mg	T300	0.30	SQC						522	84	0.6	[109]	As cast
c.p. Mg	T300	0.35	SQC						498	80		[110]	As cast
	(untreated, unsized)	0.35	SQC						390	80		[110]	600K/216h
	T300 (surface treated)	0.35	SQC						382			[110]	As cast
		0.35	SQC						511	71		[110]	600K/216h
		0.35	SQC						422	92		[110]	600K/ /1000h
		0.35	SQC						644	86		[110]	1300 times between 600K and 295K
Mg+2Al	T300	0.30	SQC						655	89	0.8	[109]	As cast
Mg+4Al	T300	0.30	SQC						645	93	0.8	[109]	As cast
Mg+4Al	T300	0.30	SQC						629	85	0.7	[109]	T4
Mg+4Al	T300 (untreated, unsized)	0.35	SQC						638	76		[110]	As cast
		0.35	SQC						510	85		[110]	600K/216h
		0.35	SQC						650	152		[110]	600K/ /1000h
		0.35	SQC						469	76		[110]	1300 times between 600K and 295K
AZ31B Mg	Boron	0.0	Infiltration						241	45		[108]	

Table 6 (cont.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
		0.70	Infiltration						2255	285		[108]	
ZK Mg	Boron	0.0	Infiltration							45		[108]	
		0.70	Infiltration						1048	296		[108]	
HZK Mg	Boron	0.0	Infiltration						276	45		[108]	
		0.70	Infiltration						1089	300		[108]	
ZA12(Zn+ +11Al+1Cu)	Al_2O_3 (Saffil)	0.00	RHE/CC						300	87	5	[111]	
		0.20	RHE/CC						238	103	1	[111]	
ZA27 (Zn+ +27Al+2Cu)	SiC_p	0.00	RHE/CC						410	73	2	[111]	
		0.10	RHE/CC						396	92		[111]	
		0.16	RHE/CC						305	113		[111]	
		0.20	RHE/CC						330	110		[111]	
		0.50	RHE/CC						310	220		[111]	
	Al_2O_3 (Saffil)	0.20	RHE/CC						220	76		[111]	
Zn+27Al+3Cu	SiC (Nicalon)	0.00	SQC	455	810	139	60–90	358	411	76	17	[101]	Chopped fibers
		0.10	SQC						300	98	2	[101]	
		0.18	SQC						265	96	1	[101]	

1) Names of the fabrication methods mentioned here are those used in the source materials
2) Preform (or die) preheating temperature
3) Pouring temperature of molten metal
4) Pressure applied on molten metal
5) Yield strength or 0.2% proof stress
6) Ultimate tensile strength
7) Young's modulus
8) Elongation
9) Squeeze casting
10) Strain to fracture
11) Pressure casting
12) Liquidus
13) Compocasting
14) Rheocasting.

w - whiskers
p - particulates.

Table 7:

Fatigue life (strength) of cast metal matrix composites

Matrix	Fiber	V_f	Fatigue life (No. of cycles)	Source (reference)	Remark
Al+4.5 Cu	SiC (Nicalon)	0.00	5.68×10^5	[101]	Vortex mixing
		0.10	9.55×10^5	[101]	Squeeze casting
Al+3.75 Mg	Al_2O_3(Saffil)	0.00	7.1×10^5	[103]	Squeeze casting
		0.02	6.97×10^5	[103]	Squeeze casting
		0.04	7.61×10^5	[103]	Squeeze casting
		0.06	8.70×10^5	[103]	Squeeze casting
		0.08	9.51×10^5	[103]	Squeeze casting
		0.10	10.15×10^5	[103]	Squeeze casting
c.p. Al	Al_2O_3 (Spinel)	0.50	10^7(400 MPa)	[92]	Squeeze casting
Al+5 Cu	Al_2O_3(Spinel)	0.50	10^7 (250 MPa)	[92]	Squeeze casting
Zn+27 Al+3 Cu	SiC_{pcs}	0.00	2.48×10^5	[101]	Squeeze casting
		0.10	4.48×10^5	[101]	Squeeze casting

Table 8:

Properties of examined materials [106]

Material / Properties	Lead		Lead infiltrated carbon felt
	Gravity	Squeeze	
Density d, g/cm^3	11.262	11.273	8.02
Proof stress $R_{0.02}$, MPa	8.16	9.35	18.26
$R_{0.05}$, MPa	8.21	9.4	18.72
$R_{0.1}$, MPa	8.3	9.5	19.5
$R_{0.2}$, MPa	8.5	9.7	18.3
Tensile strength R_m, MPa	16.1	17.57	28.76
Accommodation limit 1) R_a, MPa	7.74	9.35	18.26
Fatigue limit 2) Zg_O, MPa	5.6	6.1	10.85
Elongation A_5,%	18.65	23.53	1.3
Hardness, HB	6.1	6.3	10.3
Electrical conductivity, MS/m	4.8	4.8	4.7
Modulus of elasticity, MPa	13000	14000	17000

1) Accommodation limit – possibly highest stress which–when applied cyclically–stabilizes the permanent stress.

2) Estimated value.

Table 9:

Properties of SiC and Al_2O_3 reinforcement

Property / Particle	Modulus of elasticity GPa	Density g/cm^3	Coefficient of thermal expansion $10^6 \times K^{-1}$	Specific heat $J \times kg^{-1} K^{-1}$	Thermal conductivity $W \times m^{-1} \times K^{-1}$	Poisson ratio
SiC	420–450	3.20	4.30	840.00	10–40 at 1100°C	0.17
Al_2O_3	380–450	3.96	7.0	1050.00	5–10 at 1000°C	0.25

Table 10:

Typical applications of particulates reinforced MMCs

Application	Matrix	Reinforcement
Self lubricating applications	Al, Mg, Pb–Sn	graphite, mica
Wear resistance applications:		
– medium severity	Al	Al_2O_3, SiC, TiC, SiO_2, B_4C, ZrO_2
– high severity	Fe–Cu	diamond WC–Co
Structural applications	Mg, Al	Al_2O_3, SiC
High temperature application	Ti	carbon, Al_2O_3, SiC
Self–lubricated electrical contacts	Cu	graphite, mica
Damping applications	Al	graphite, mica

Table 13:

Room temperature properties of particulate reinforced aluminium matrix composites [144]

Composite	**Tensile strength**	**Elongation**	**Young's modulus**	**CTEX**[1)]
	MPa	**%**	**GPa**	**10^{-6}/K**
Duralcan F3A 10 μm	303	1.0	93	16
Duralcan F3B 10 μm	317	1.0	93	16
Duralcan X3K 10 μm	351	0.5	93	16
M. Marietta 201XD 3 μm	420	1.0	93	
Duralcan C56F+10%SiC 10 μm	220	0.5	81	
Pechiney A357+15%SiC 30 μm	303	0.5	87	18
A357+25% Saffil Al	289	1.1	76	
6061+25% Saffil Al	317	1.1	76	
A357+17% SiC whisker	303	1.1	49	
A357+40% SiC whisker	255	0.9	49	
6061+17% SiC whisker	344	1.6	59	
6061+40% SiC whisker	282	0.9	56	
A357+45% SiC part.	310	0.3	151	12
A357+65% SiC part.	207	0.2	172	8
6061+45% SiC part.	207	0.2	100	13
6061+65% SiC part.	200	0.1	158	9
A357+25% SiC fiber	620	0.3	193	
6061+25% SiC fiber	310	0.4	110	

The above figures are included only to give a brief insight into rough materials properties obtained during past casting trials. Specific figures are dependant on the selected solidification and infiltration conditions which may be varied and improved in future work.

[1)] CTEX – coefficient of thermal expansion.

Fig. 1. A Diesel engine piston, squeeze cast, with the reinforced crown part enclosing the combustion chamber. The ceramic preform based on short alumina fibers was used (TOYOTA–Japan)

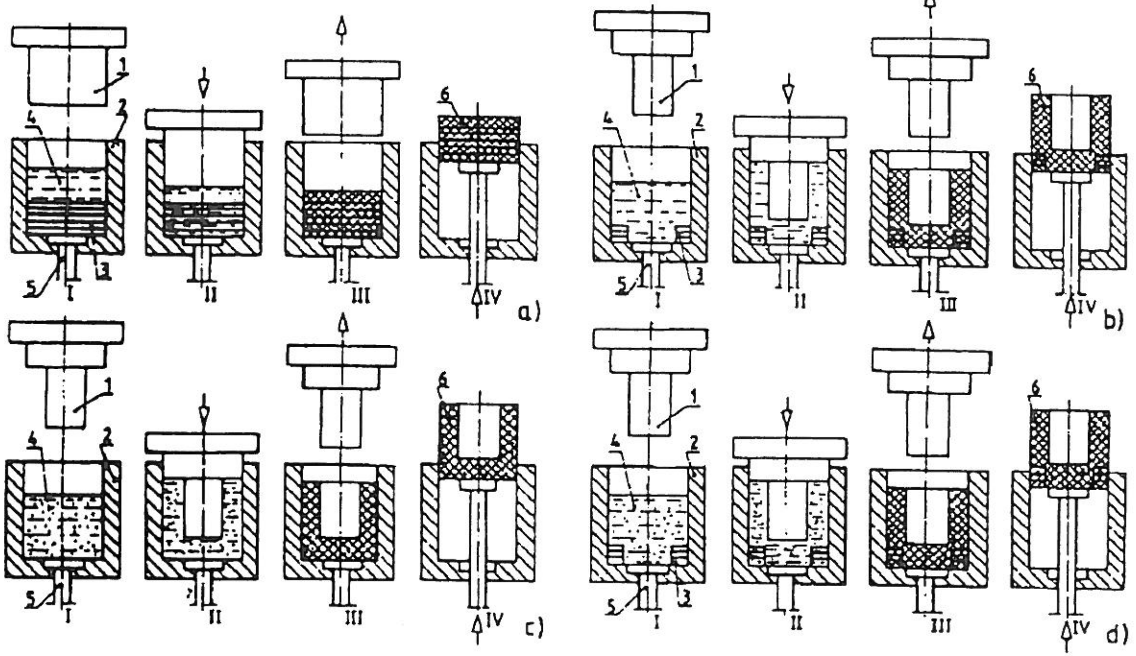

Fig. 2. Example of squeeze casting applied in the manufacture of composite products: a – pressure infiltration of preform (fibrous, skeleton, dispersion), b – making of casting reinforced with composite insert (or with simultaneous infiltration of reinforcing preform), c – making of dispersion–reinforced casting (reinforcement with particles, whiskers or short fibres), and d – making of hybrid composites (simultaneous reinforcement with preform, one or more dispersion phase). I–IV– the successive stages of process; 1 – squeeze plunger (stamp), 2 – die (lower part), 3 – preform, 4 – liquid metal (metal suspension with dispersion phase), 5 – ejector, 6 – ready composite

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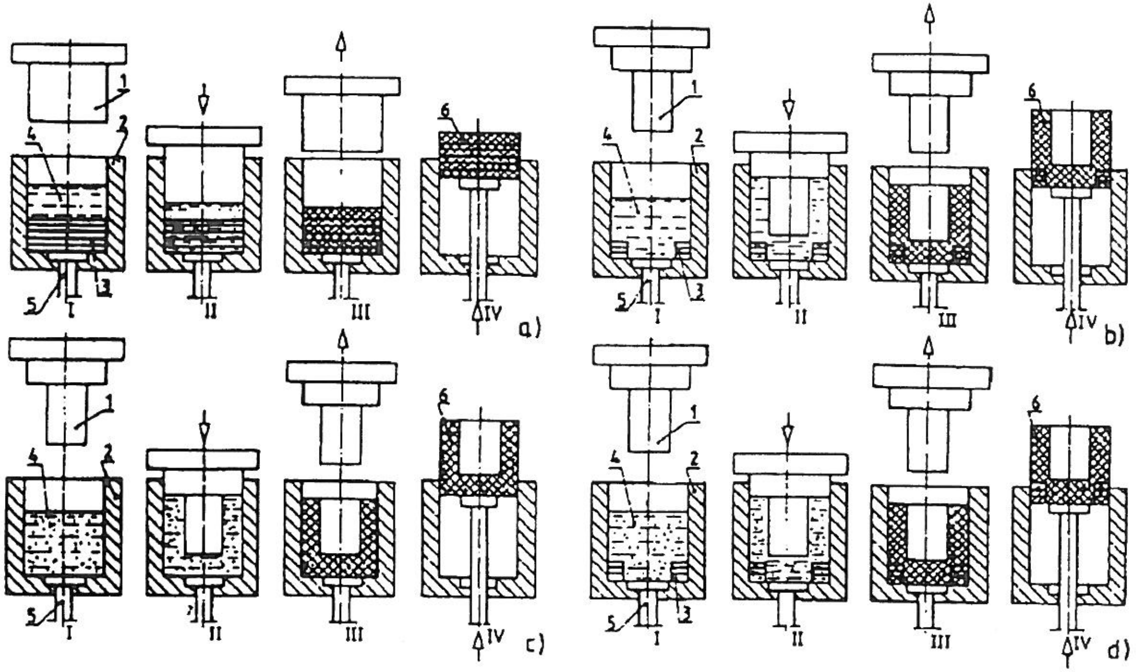

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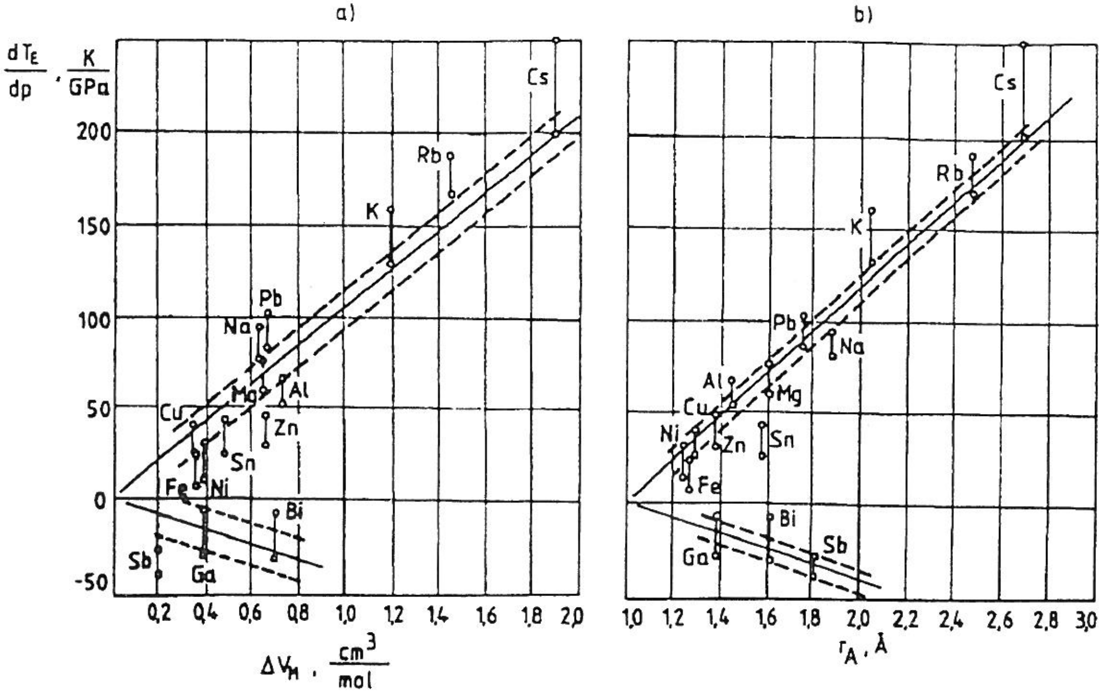


Fig. 3. Relative variations in the pressure-affected melting temperature of metals vs. relative molar change in the specific volume (a) and atomic ratio (b). The data given in [43] were used

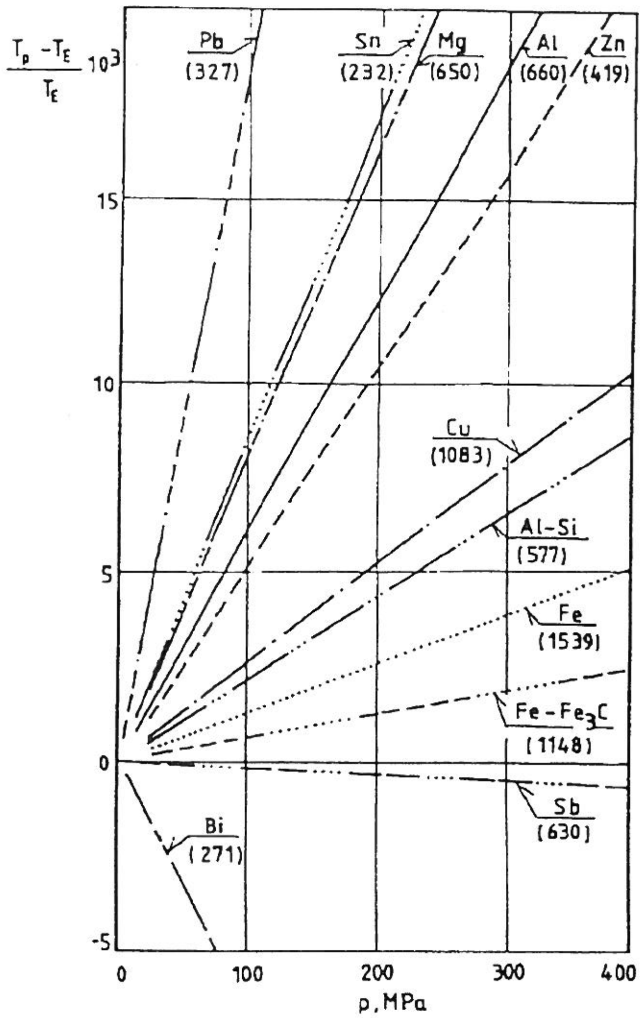


Fig. 4. Effect of pressure on relative variation in the solidification (melting) temperature of metals and Al–Si and Fe–Fe$_3$C eutectics (plotted from the experimental data described in [43]); T_p – melting temperature of metal under pressure p; T_E – equilibrium temperature of melting and solidification. The numbers under the symbols of elements stand for the value of melting temperatures under atmospheric pressure (°C)

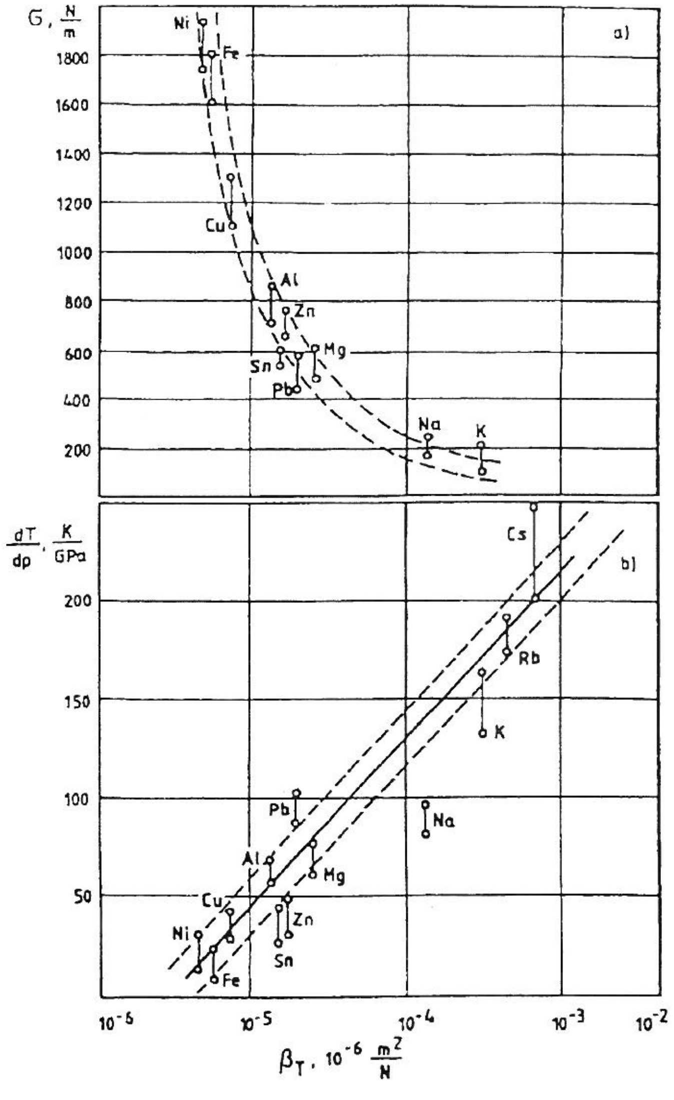


Fig. 5. Surface tension at a near–solidification point temperature (a) and increase in the solidification temperature (melting point) of pure metals under the effect of pressure $\frac{dT}{dp}$ (b) vs. the coefficient of isothermal compressibility (after the data given in [43]); taking into consideration the scatter of data, including the data from computations

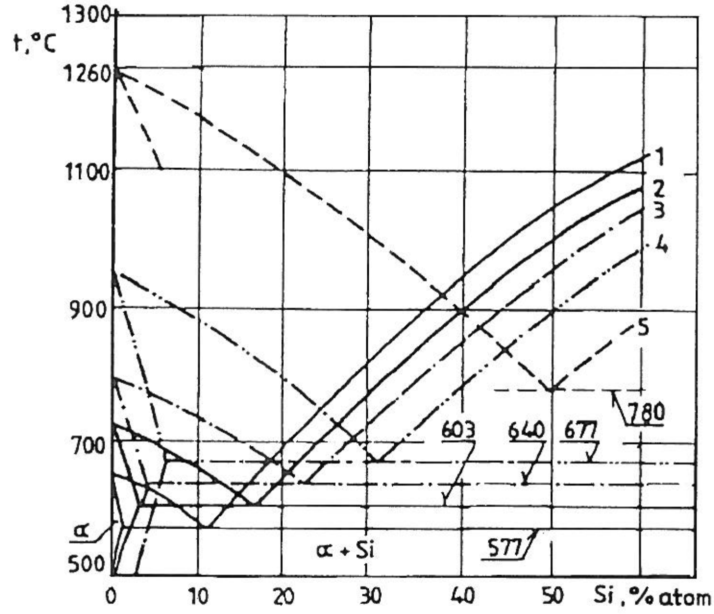


Fig. 6. Effect of pressure on the phase equilibrium diagram in Al–Si system: 1 – atmospheric pressure (0.1 MPa), 2 – 1 GPa, 3 – 2.5 GPa, 4 – 5 GPa, 5 – 10 GPa

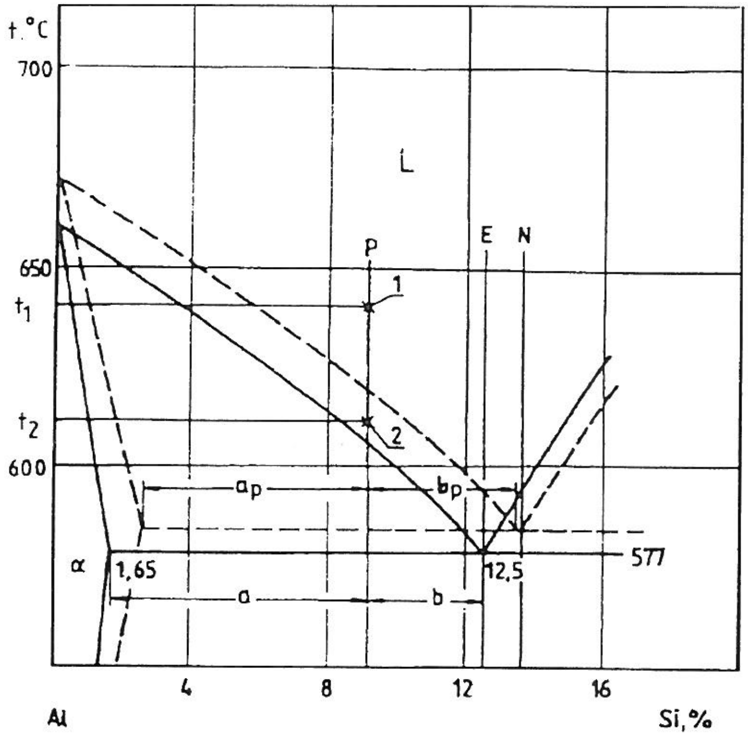


Fig. 7. The phase equilibrium diagram of an Al–Si system with plotted lines of the pressure–induced transformations of a few hundred MPa [43]

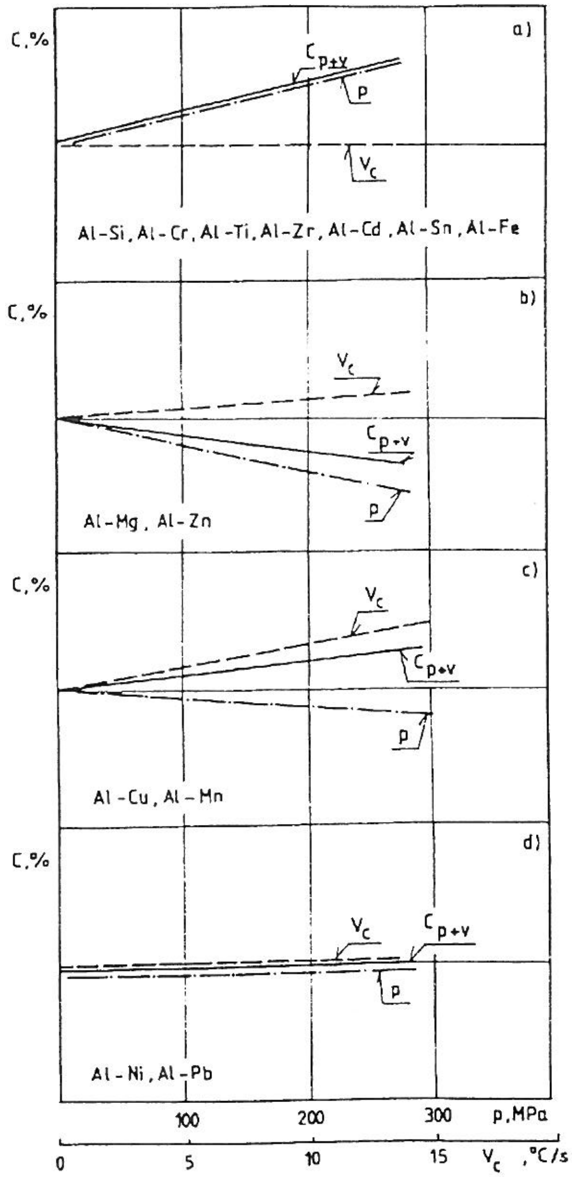


Fig. 8. Schematic representation of an effect of cooling rate (*v*), pressure (*p*) and crystallization under pressure on the content of alloying element (*c*) in the aluminium-based solid solution. Plotted after [69]

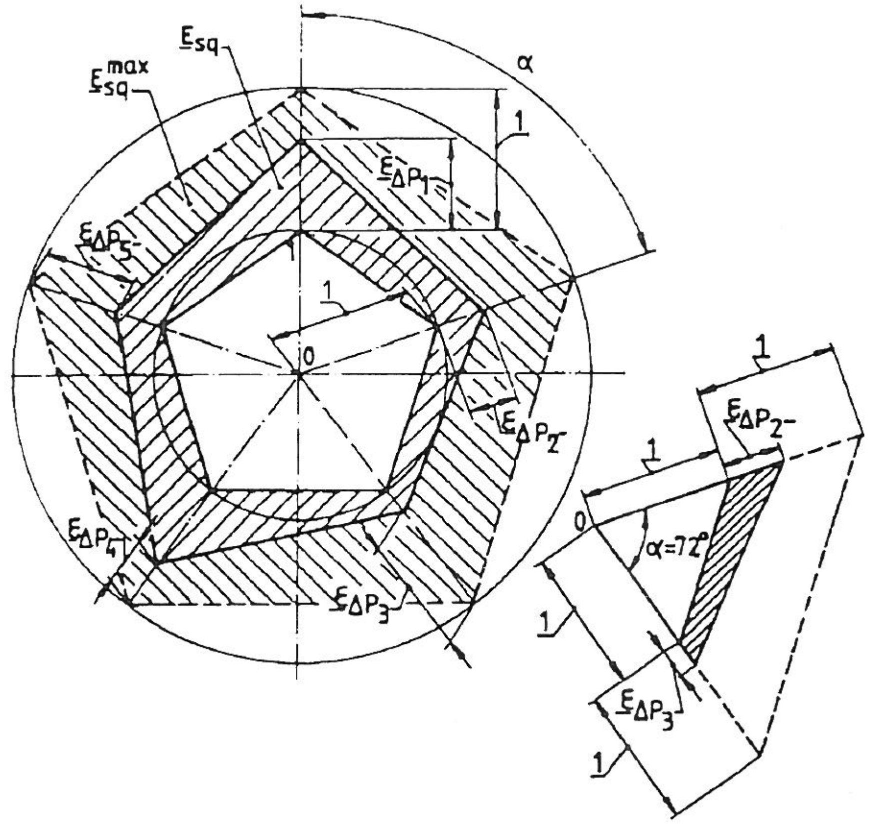


Fig. 9. Schematic representation of a method to determine the squeeze efficiency factor E_{sq} for the five examined properties [43]

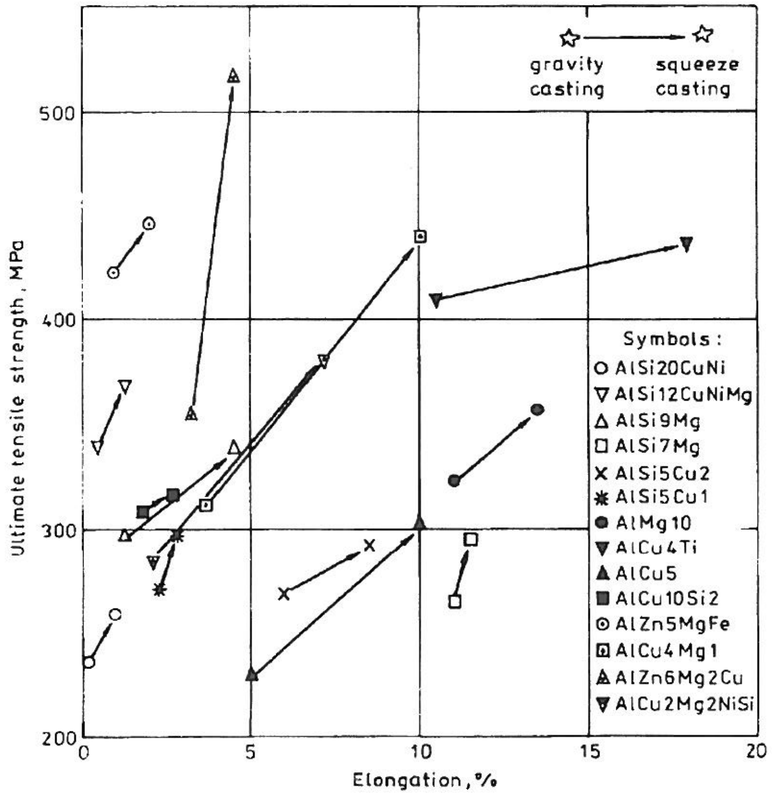


Fig. 10. Tensile test data of cast aluminium alloys fabricated by gravity casting and by casting under pressure of 120 MPa (after heat treatment) [43]

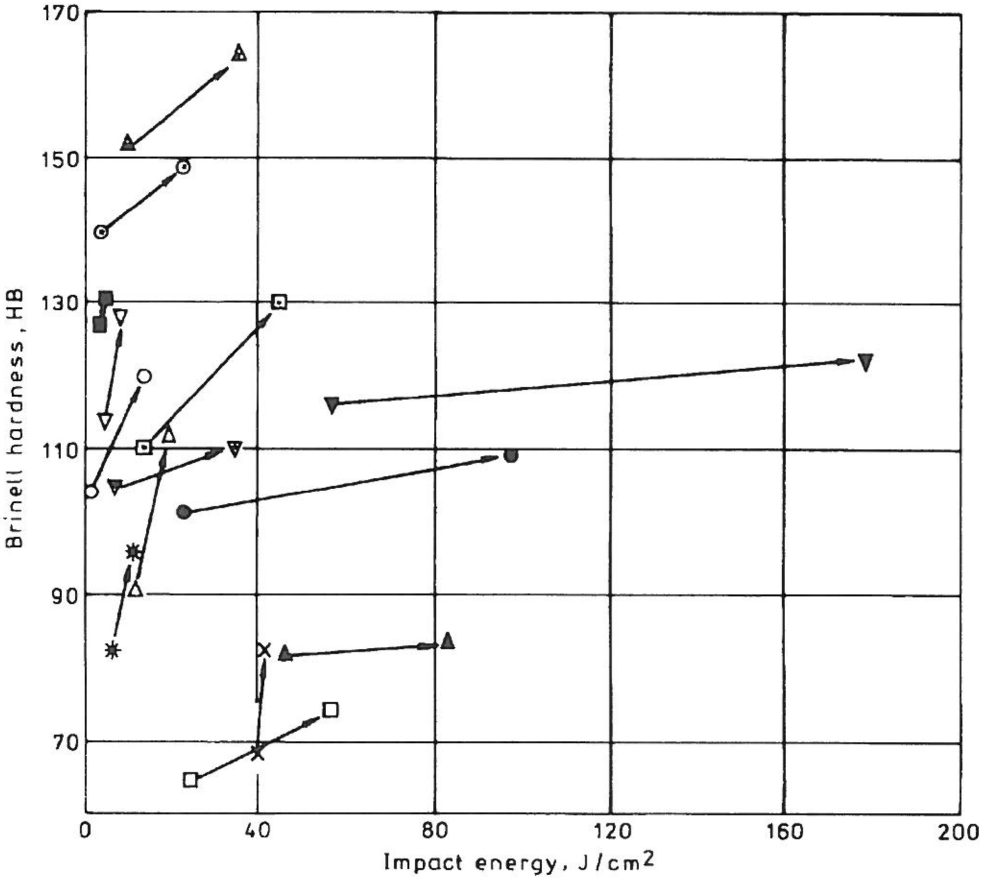


Fig. 11. Brinell hardness and impact energy data of cast aluminium alloys fabricated by casting and by squeeze casting under pressure of 120 MPa (after heat treatment) [43]

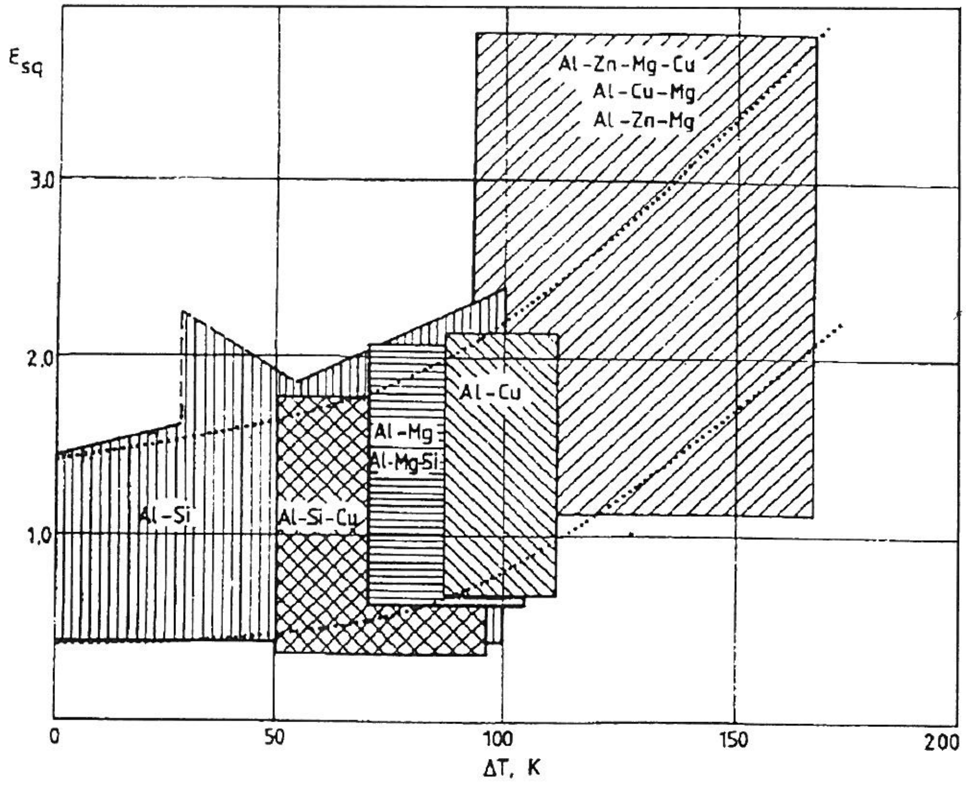


Fig. 12. Schematic representation of a relationship between the squeeze efficiency factor E_{sq} and solidification range of alloys with phase equilibrium diagrams ascribed to certain base regions. The values of E_{sq} depend on the population of the examined alloys and on the number of tested properties (on the axis of ordinates the approximate values are given) [43]

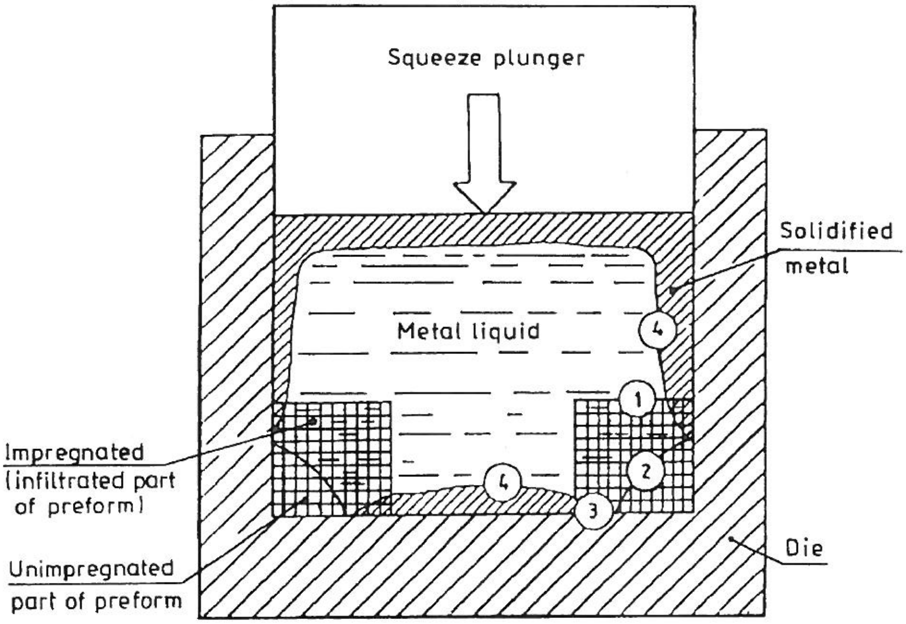


Fig. 13. Schematic representation of making a composite element by squeeze casting with "bottom" infiltration of preform: 1 – access of metal liquid to the preform surface, 2 – infiltration front, 3 – interaction at the casting–die interface, 4 – solidification front (after [79])

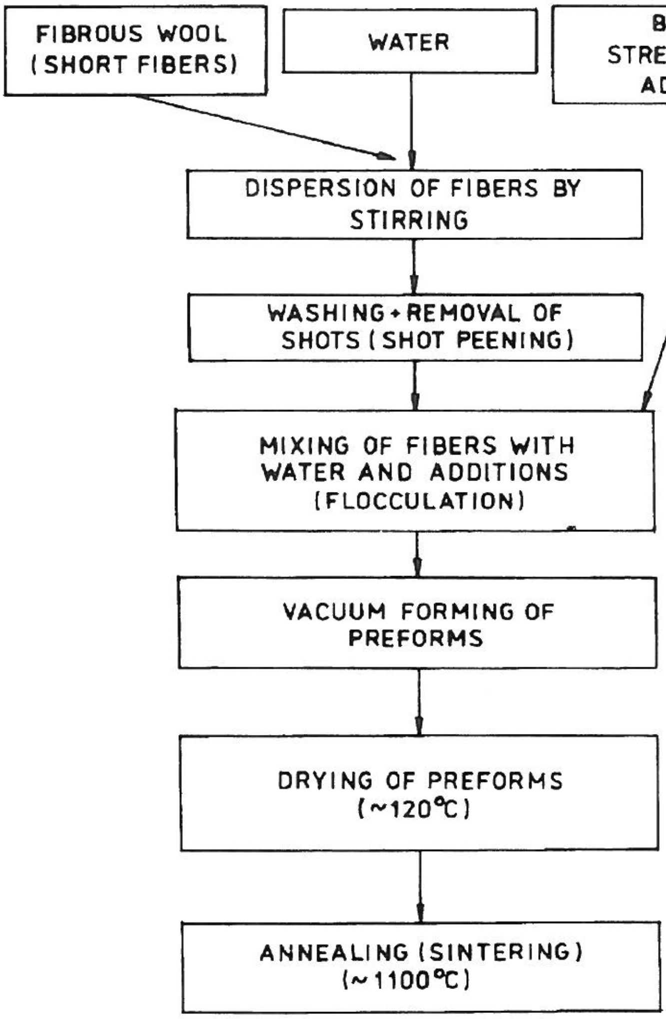


Fig. 14. Schematic representation of the process of making ceramic fiber preforms, developed by the Foundry Research Institute, Kraków

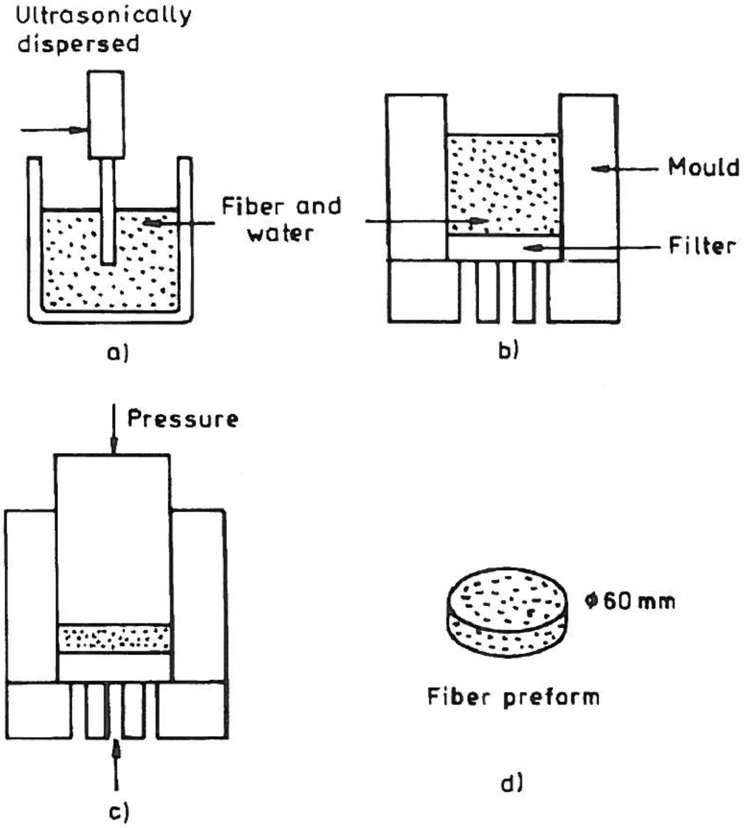


Fig. 15. The process of manufacturing the fibre preforms

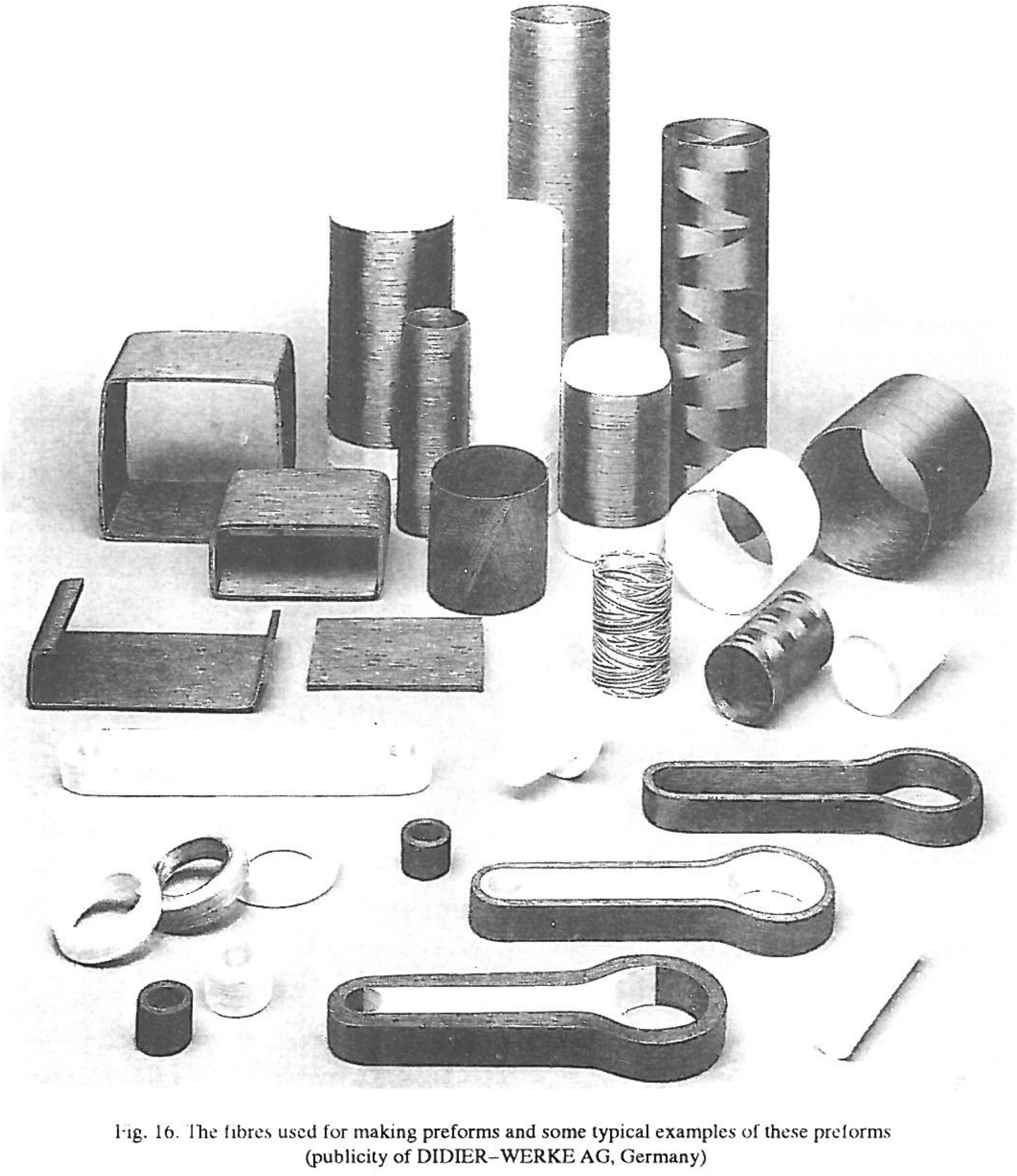


Fig. 16. The fibres used for making preforms and some typical examples of these preforms (publicity of DIDIER–WERKE AG, Germany)

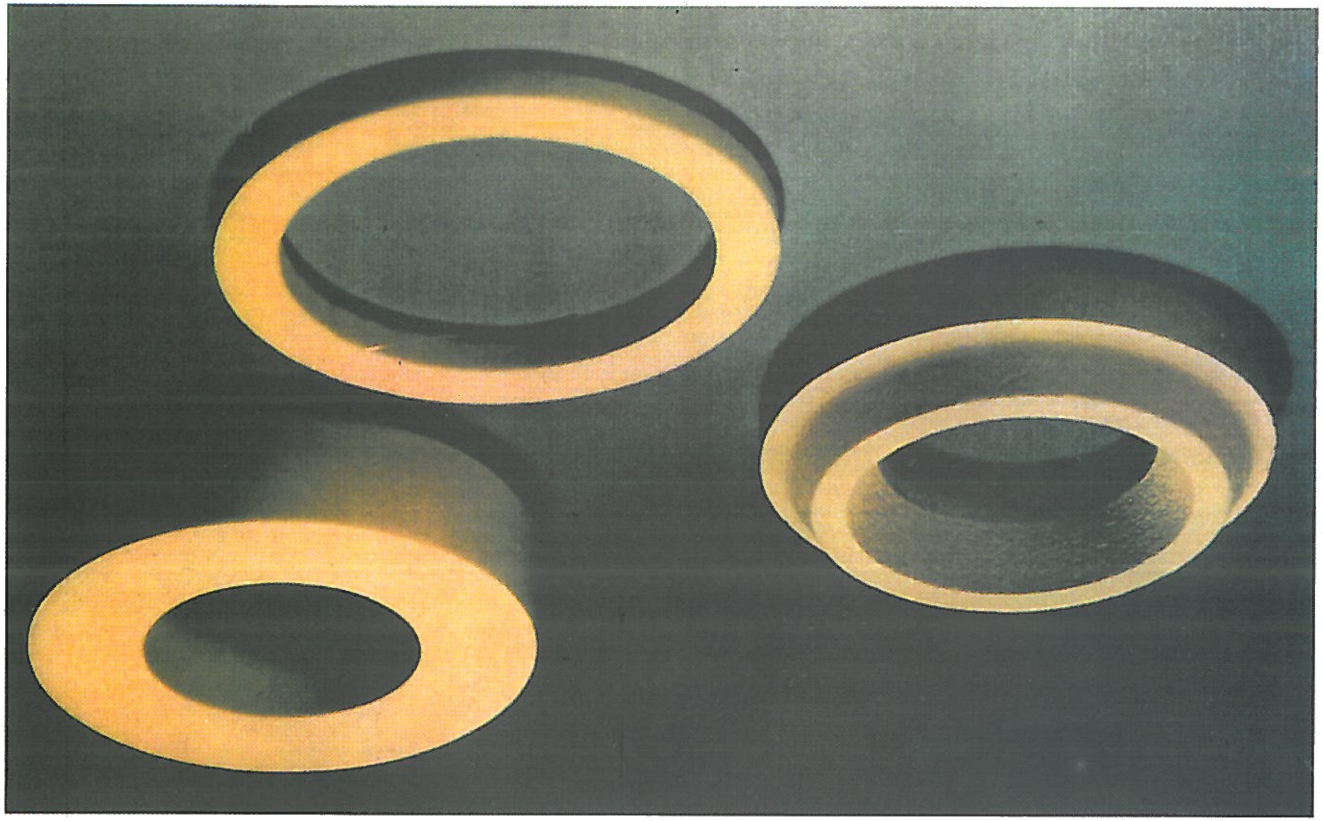


Fig. 17. Porous fiber preforms used for local reinforcement of I.C. engine pistons. DIDIER-WERKE AG, Germany; short fibers of Al_2O_3

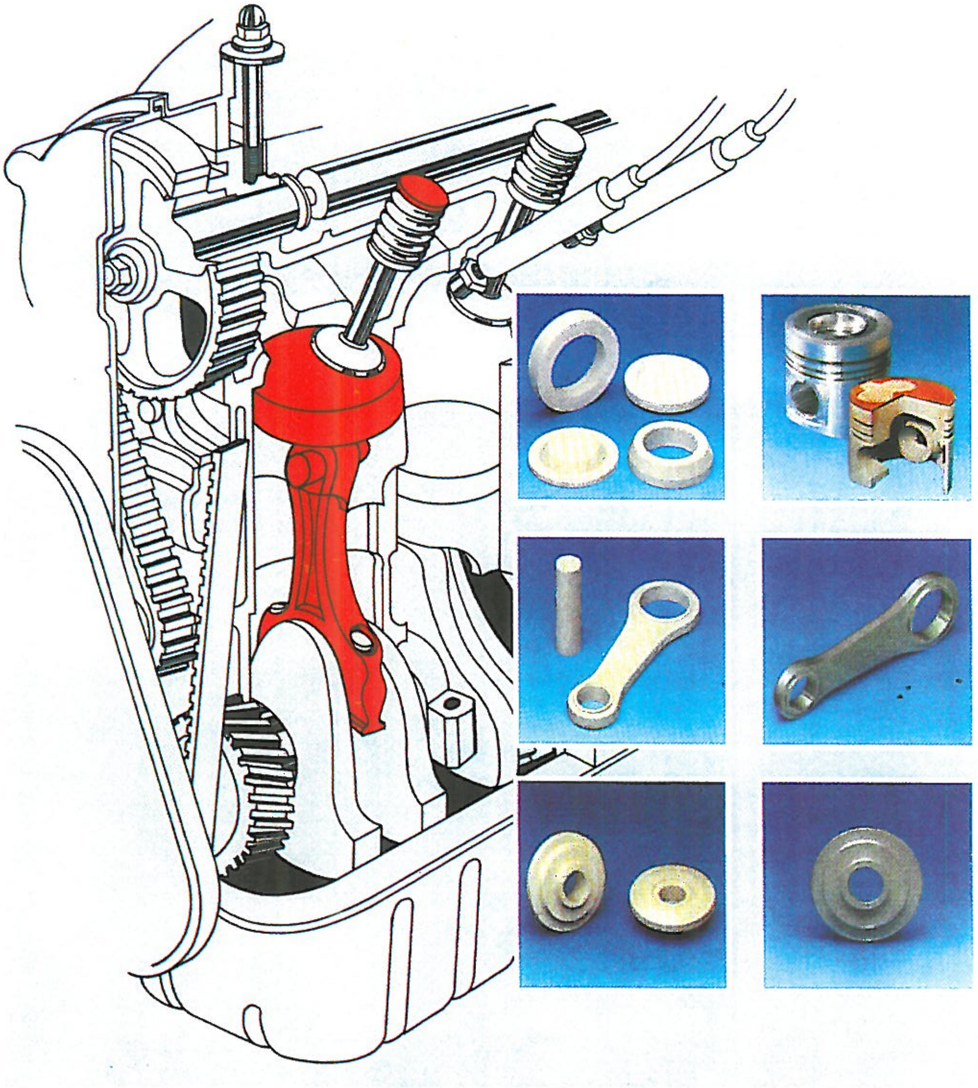


Fig. 18. Possible applications in an I.C. engine of cast metal matrix composites (CMMCs) fabricated by squeeze casting (DIDIER–WERKE AG, Germany)

Fig. 19. A Perkins type high–duty truck engine piston, squeeze cast, with local reinforcement by the alumina–based preforms; made by KOLBENSCHMIDT AG, Germany; matrix alloy: AlSi12CuMg

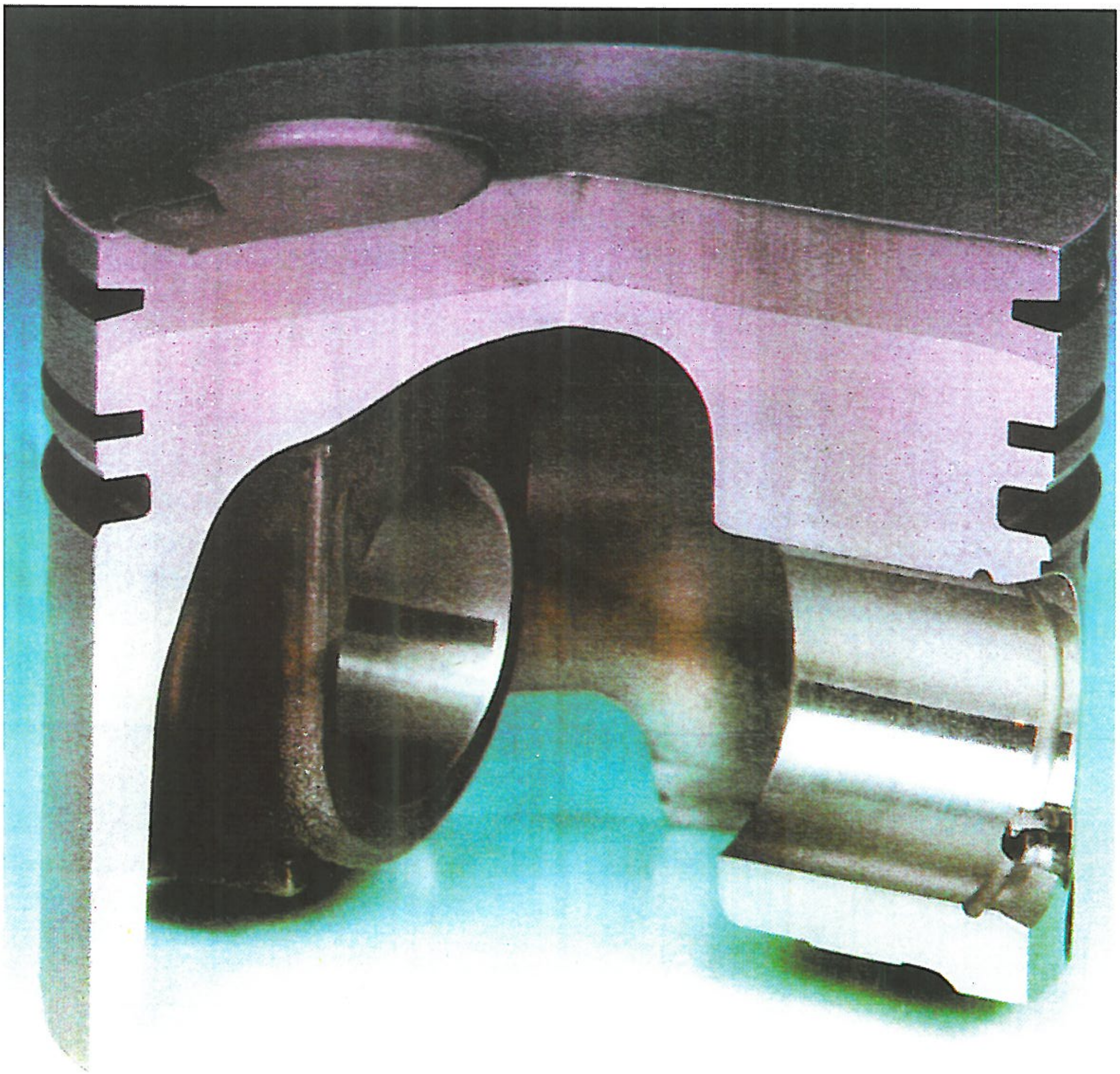


Fig. 20. An IVECO composite piston with local reinforcement by alumina–based ceramic fiber preform, impregnated in the squeeze infiltration process. The local reinforcement covers the whole surface of the piston crown and penetrates inside to a depth enabling the first ring to be inserted in the composite. The piston is running in a high–duty truck engine. Matrix alloy: AlSi12CuMgNi. Made by KOLBENSCHMIDT AG

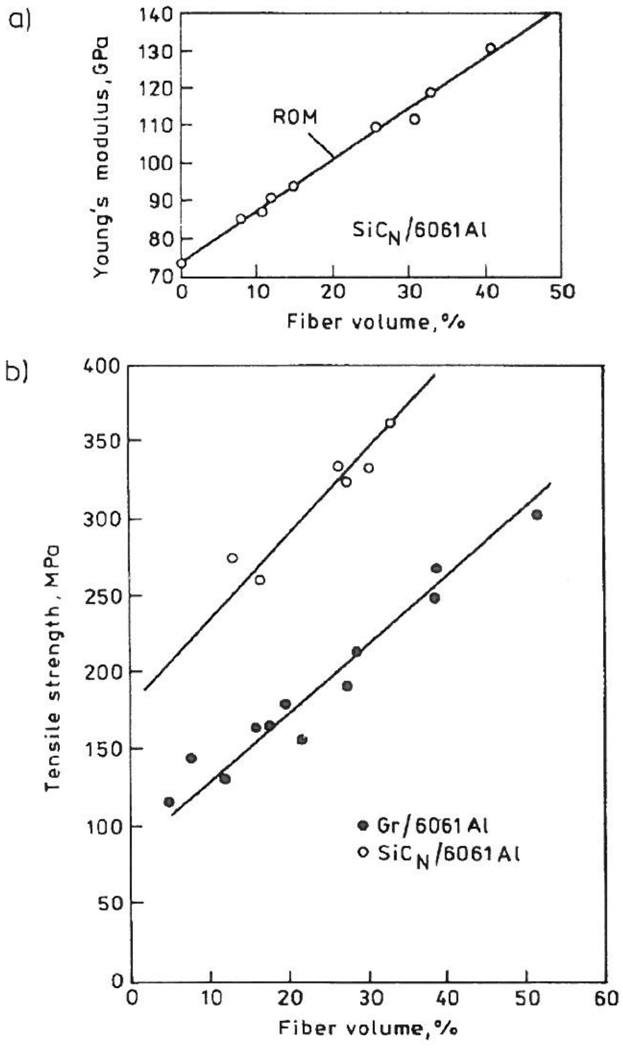


Fig. 21. Tensile stiffness (a) and strength (b) of unidirectional composites fabricated by squeeze casting ROM–rule of mixture

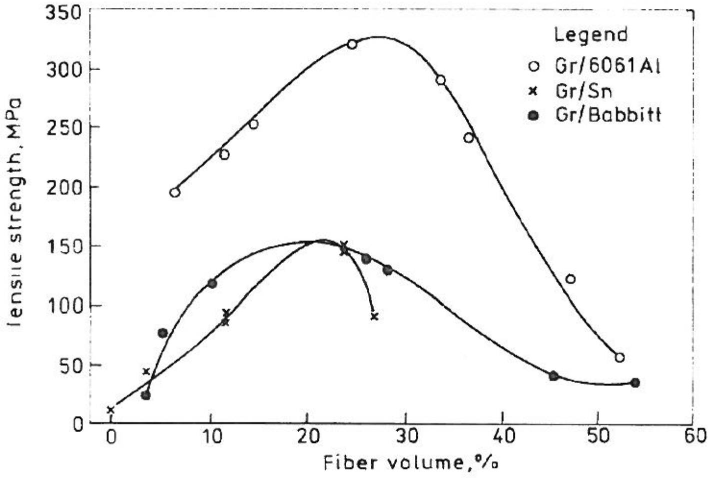


Fig. 22. Tensile strength of planar-random graphite fiber-reinforced metal matrix fabricated by squeeze casting

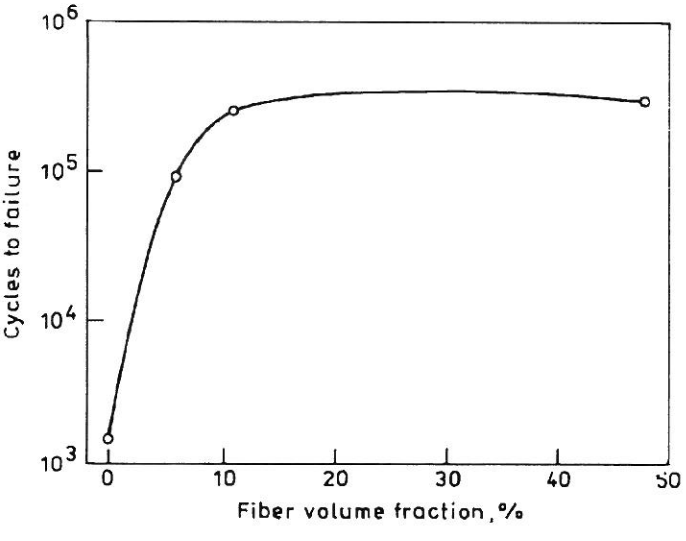
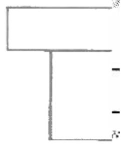


Fig. 23. Low-cycle fatigue life of planar-random graphite (nickel-coated) fiber-reinforced 6061 aluminium matrix composites fabricated by squeeze casting [75]



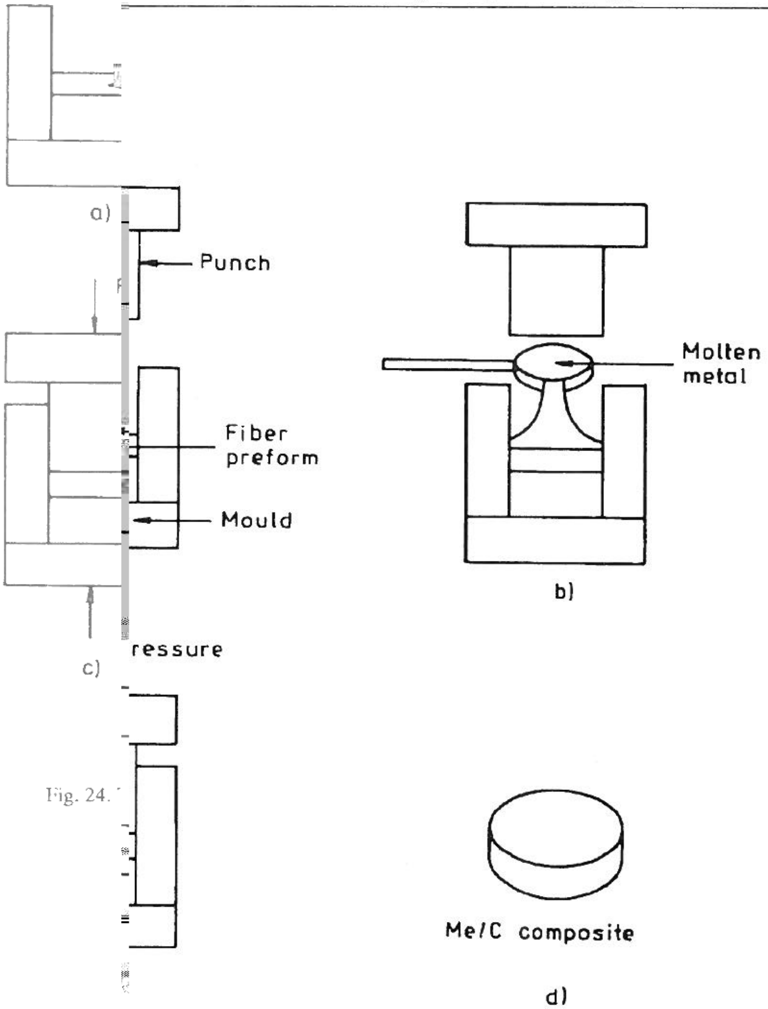


Fig. 24.

he process of squeeze casting (squeeze infiltration of preform)

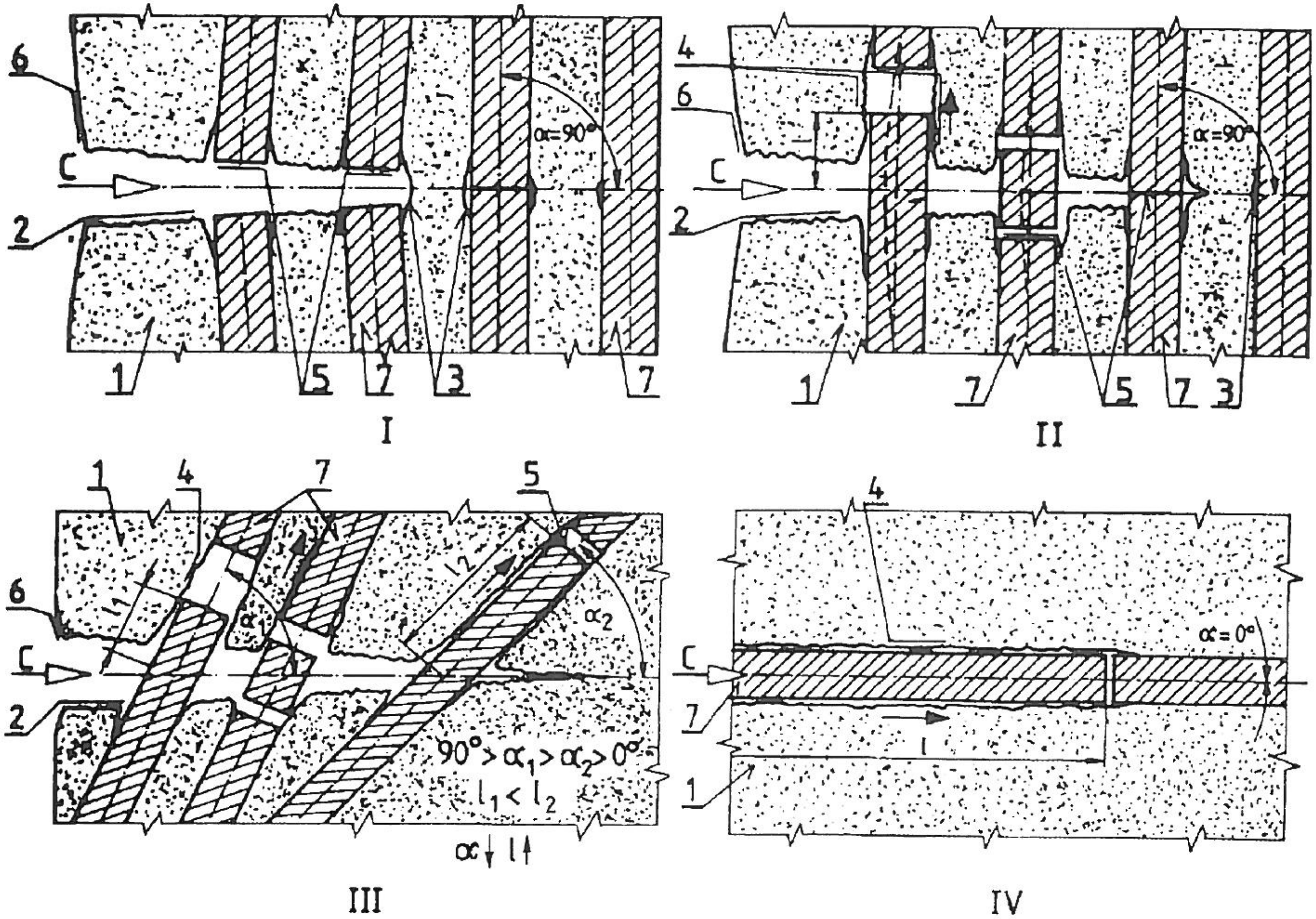


Fig. 25. A model of fracture process in fiber–reinforced composite: 1 – ductile matrix, 2 – ductile matrix fracture, 3 – fracture front at the phase boundary, 4 – sliding (the splitting starts to form), 5 – fiber rupture, 6 – matrix fracture neck, 7 – carbon fiber; α – angle between fiber axis and orientation of fracture propagation; l – fiber length from the axis of fracture propagation; c – orientation of fracture propagation

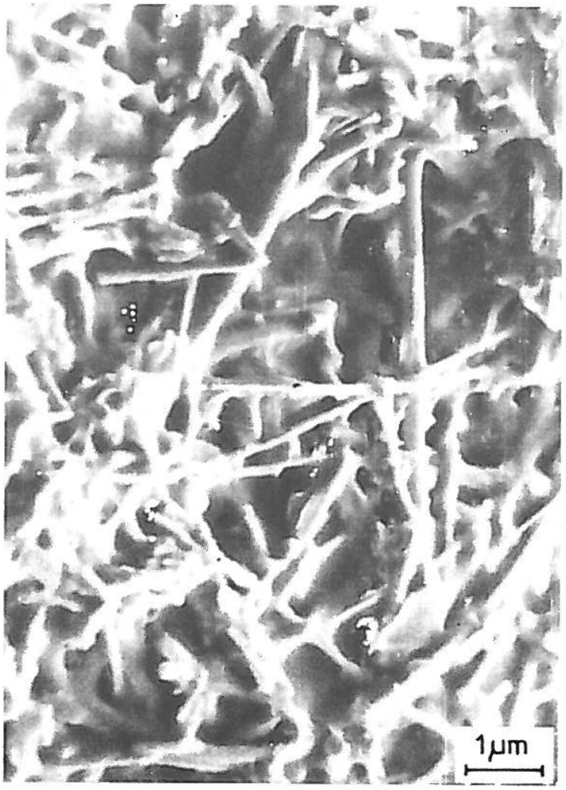


Fig. 26. The structure of a short Al_2O_3 fiber preform. From the collection of the Foundry Research Institute

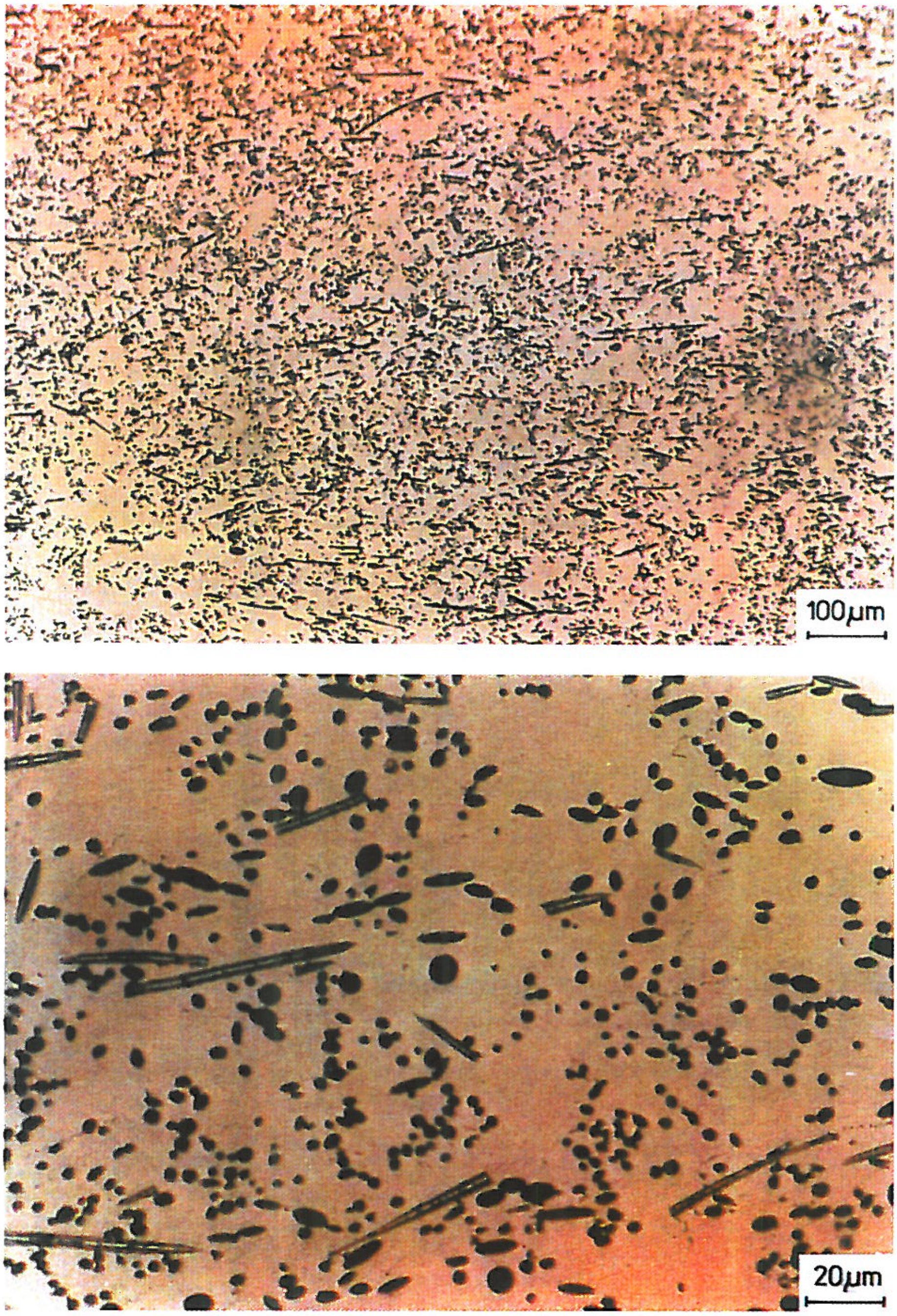


Fig. 28. Microstructure of aluminium alloy reinforced with porous preform by squeeze casting in the Foundry Research Institute (preform made from short Al_2O_3 fibers in DIDIER WERKE AG, Germany)

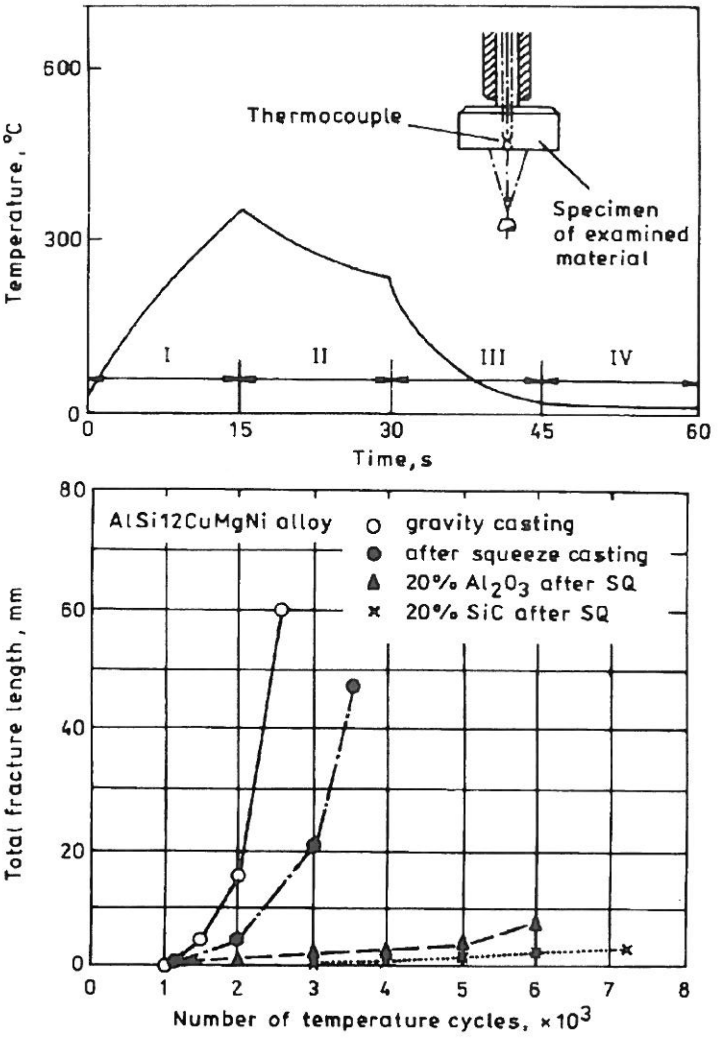


Fig. 29. The result of thermal shock resistance tests carried out on an AlSi12CuMgNi(KS1275) alloy–monolithic (gravity cast and squeeze cast) and reinforced with Al_2O_3 and SiC preforms. The axial–symmetrical specimens of the examined materials were subjected to changing temperature cycles according to a pre–established programme: I – heating, II – cooling in the air, III – cooling in water, IV – drying in the air. From the data of KOLBENSCHMIDT and DIDIER WERKE AG

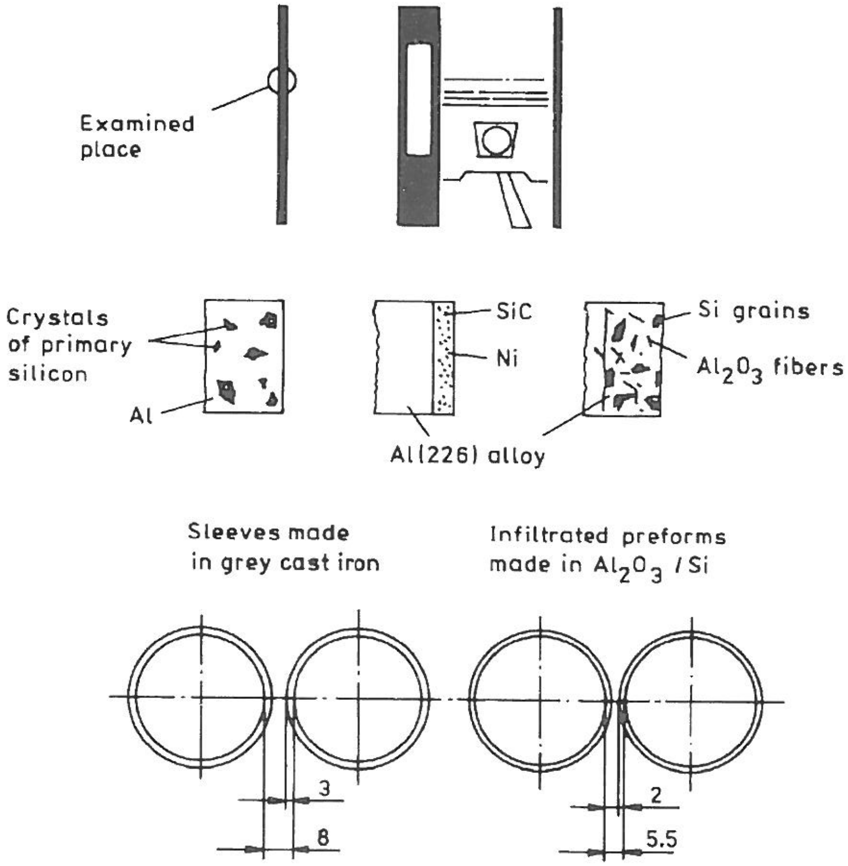


Fig. 30. An example to prove the advantages resulting from local reinforcement of an I.C. engine cylinder. The figure illustrates the successive stages of improvements in design and material of the cylinder sliding surface zone (a), possible dimensional changes in the side layer thickness (the zone of sliding surface) and in the distance between the neighbouring sliding surfaces (b) in the case of using Al_2O_3+Si preforms as compared to grey cast iron cylinder sleeves

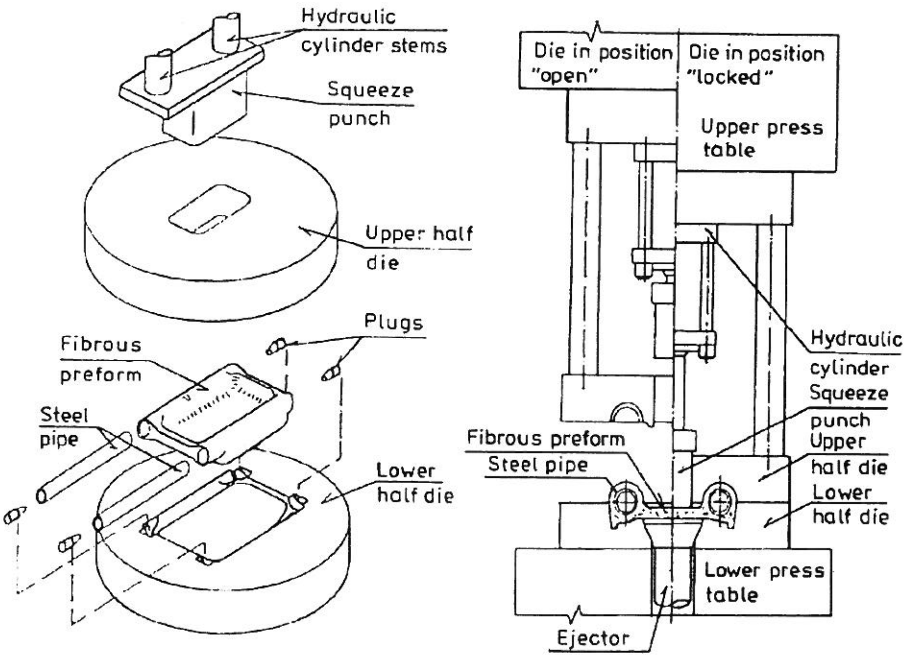


Fig. 31. Schematic representation of making the reinforced casting of a track base by pressure infiltration of preform (made of Saffil fibers) with aluminium alloy (A206); the Saffil fibers are fibers of Al_2O_3 (95%) coated with SiO_2 (5%)

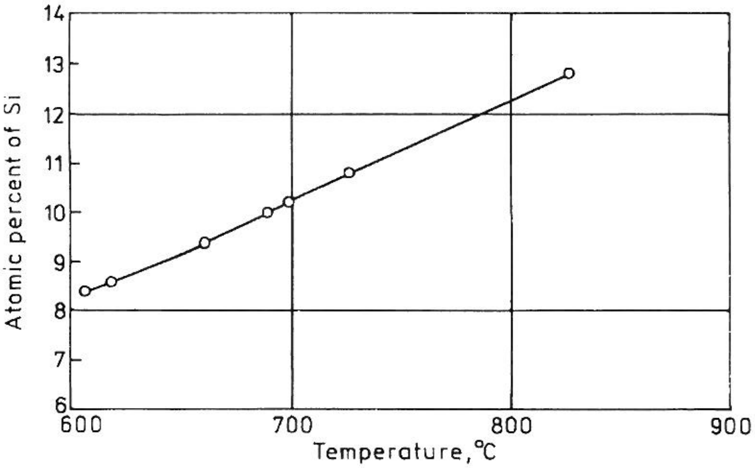


Fig. 32. Minimum silicon level to prevent aluminium carbide formation versus temperature. Thermodynamic considerations only [143]

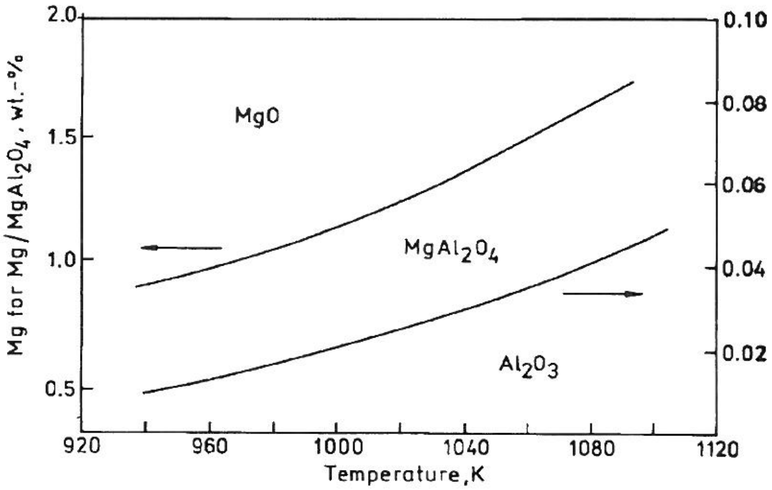


Fig. 33. Thermodynamic stability of Al–Mg oxides in Al–Mg alloys [123]

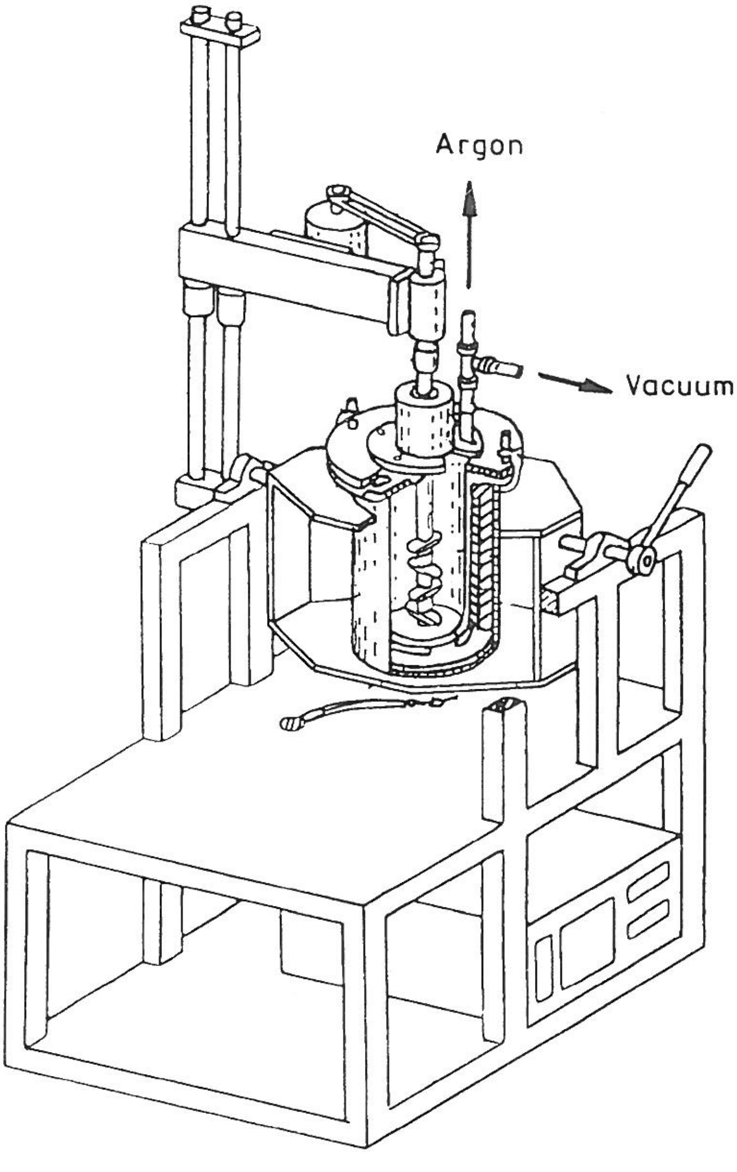


Fig. 34. Mixing vessel after the patent of M.D. Skibo and D.M. Schuster [142]

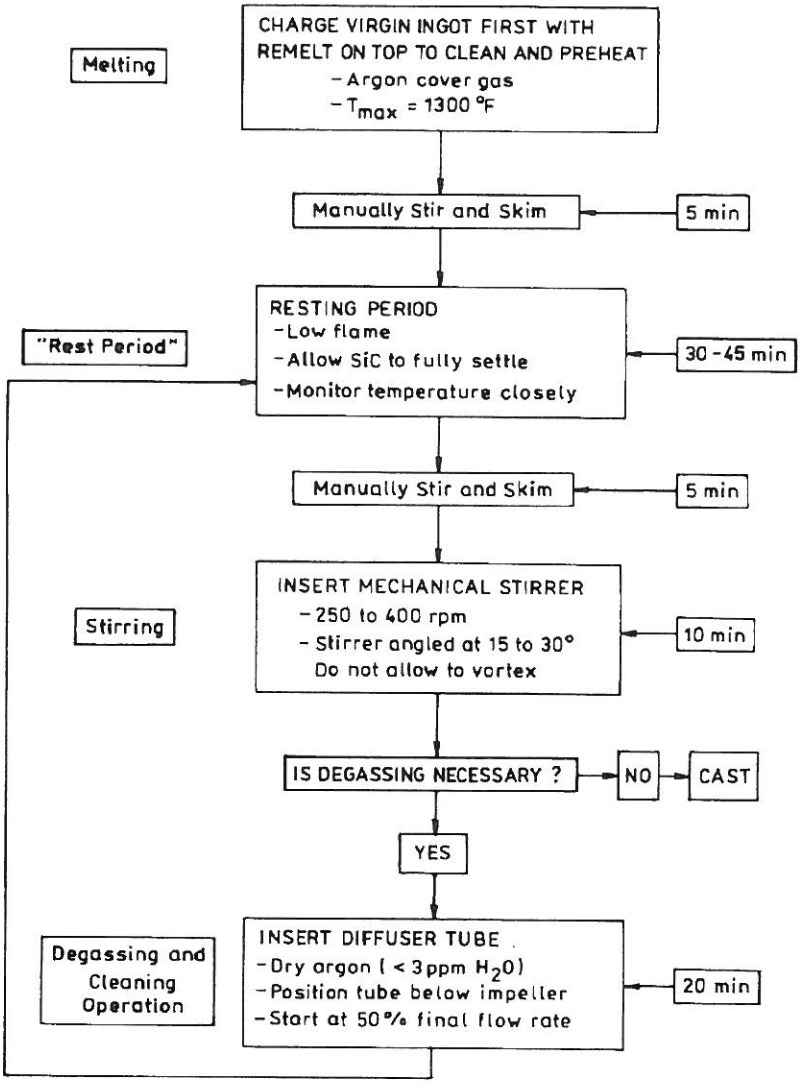


Fig. 35. Melting and recycling practice for SiC–reinforced aluminium composites [143]

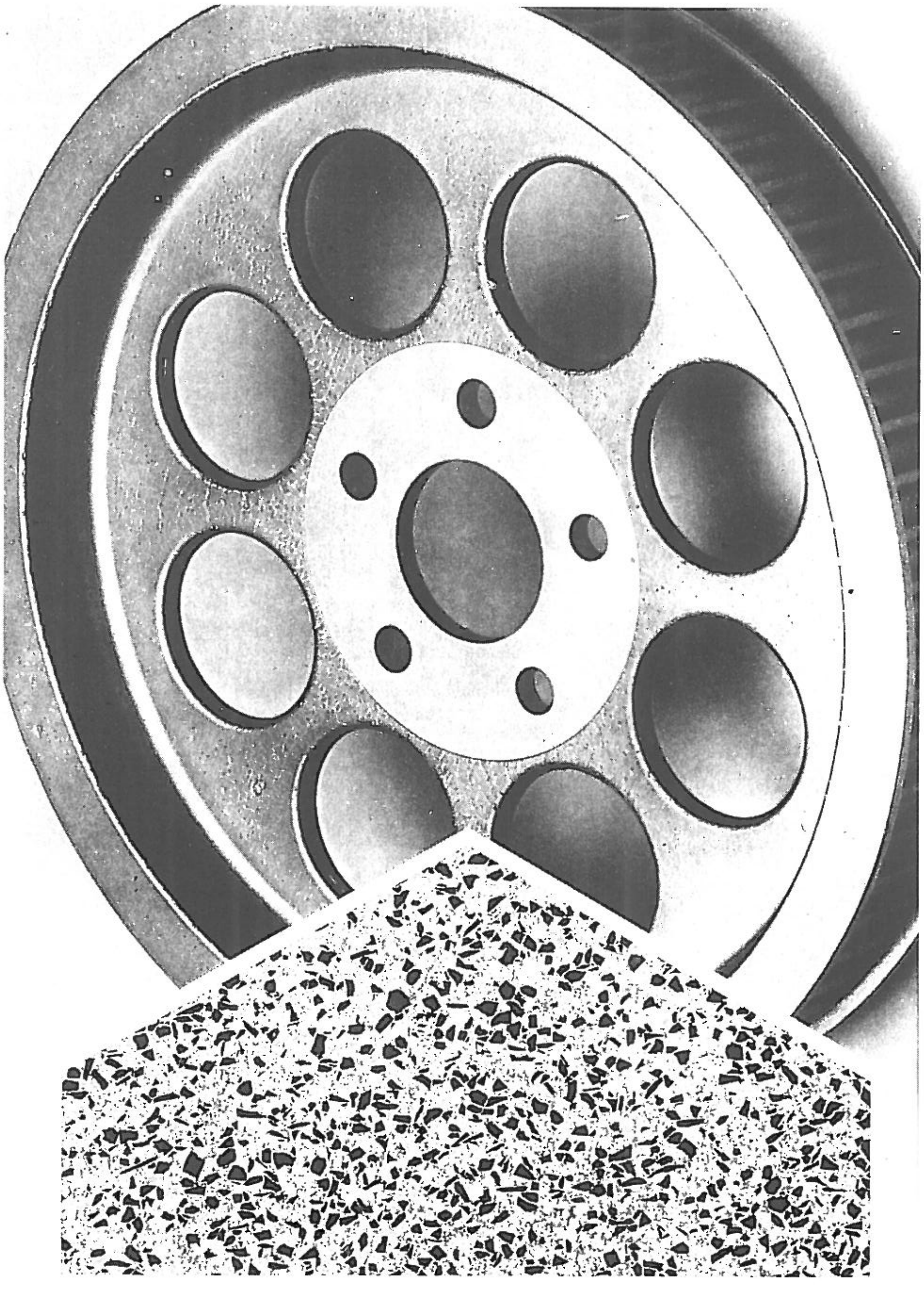


Fig. 36. Prototype of a motorcycle sprocket (320 mm – diam.) squeeze cast in DURALCAN F3D.20s by ECK INDUSTRIES, INC., Manitowac, Wisconsin. On the left: photomicrograph of composite (125x)

Fig. 37. The stand for fabrication of cast metal matrix composites in the Foundry Research Institute, Krakow The stand comprises an installation for homogenization of metal liquid under the cover of argon (on the left) and a 160 t capacity hydraulic press for squeeze casting, equipped with a die, a device for spray application of protective and parting coatings, and a set of measuring instruments for control of the thermal and force--related process parameters

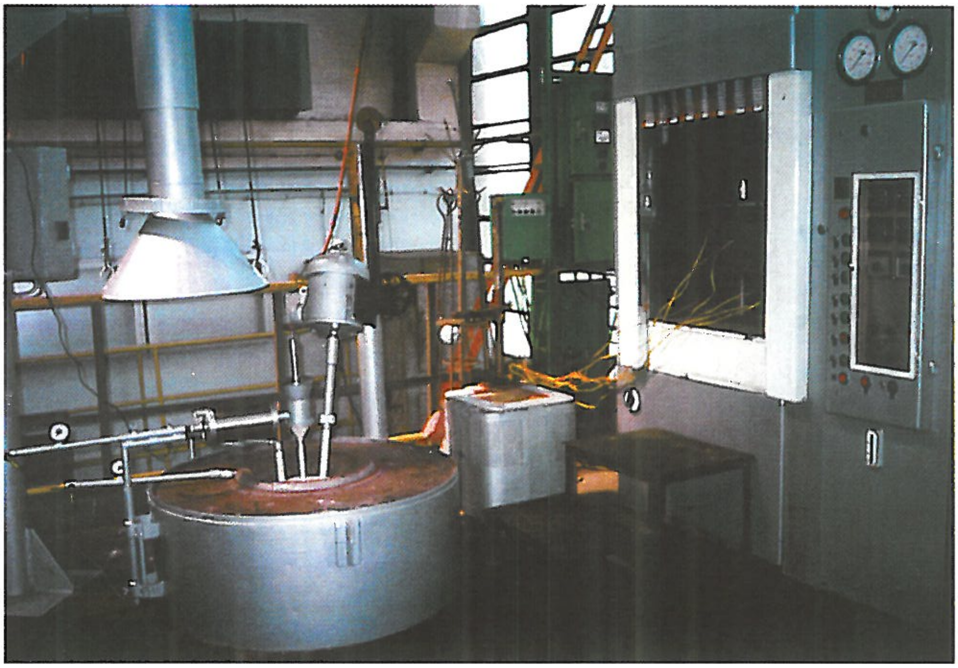


Fig. 38. A complex installation for homogenization of metal liquid (suspension) operating in a system introducing the particles of reinforcing phase and their distribution within the metal matrix volume in a crucible. The mixing arm is driven by an electric motor; the possibility of smooth change in the number of revolutions

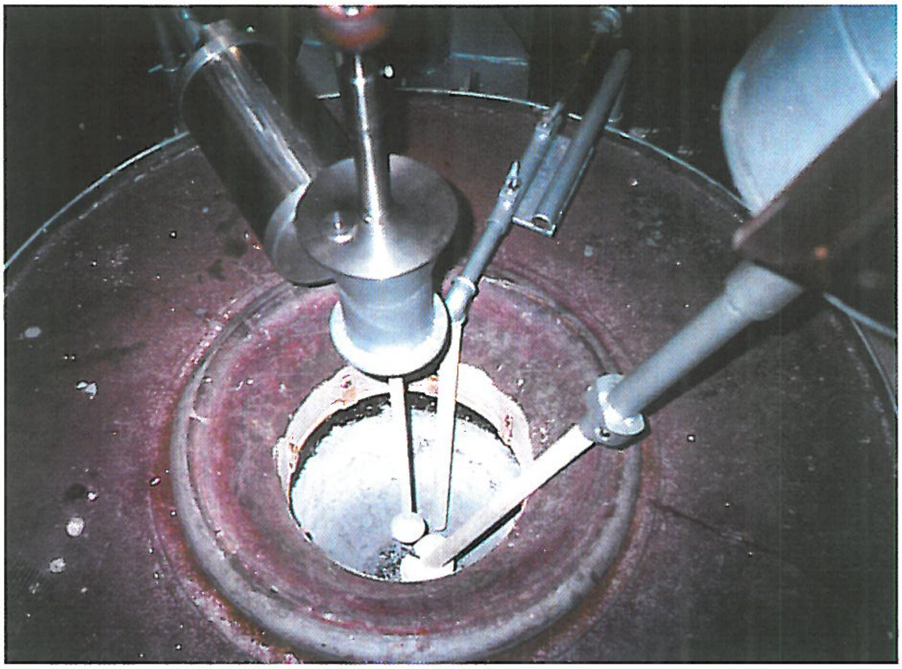


Fig. 39. A fragment of the complex installation for homogenization (suspension) operating in a system of introducing the particles into liquid metal in a stream of inert gas. From the left: argon preheating installation, a vessel with reinforcing phase, a thermocouple and a mixing arm. On the external side of the furnace cover a coil feeding the inert gas directly to the metal surface has been mounted

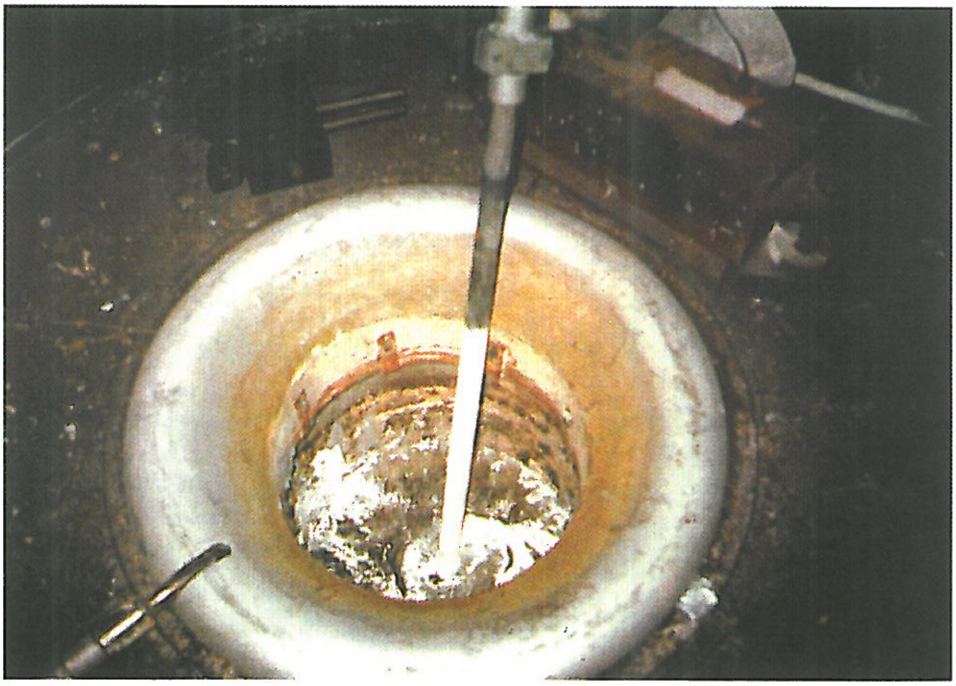


Fig. 40. Mixing of the liquid particulates reinforced composite to obtain a homogeneous distribution of reinforcing phase in the metal matrix

Fig. 41. A crucible with the liquid particulates reinforced composite. The operation of mixing completed. The liquid composite is ready for further recycling

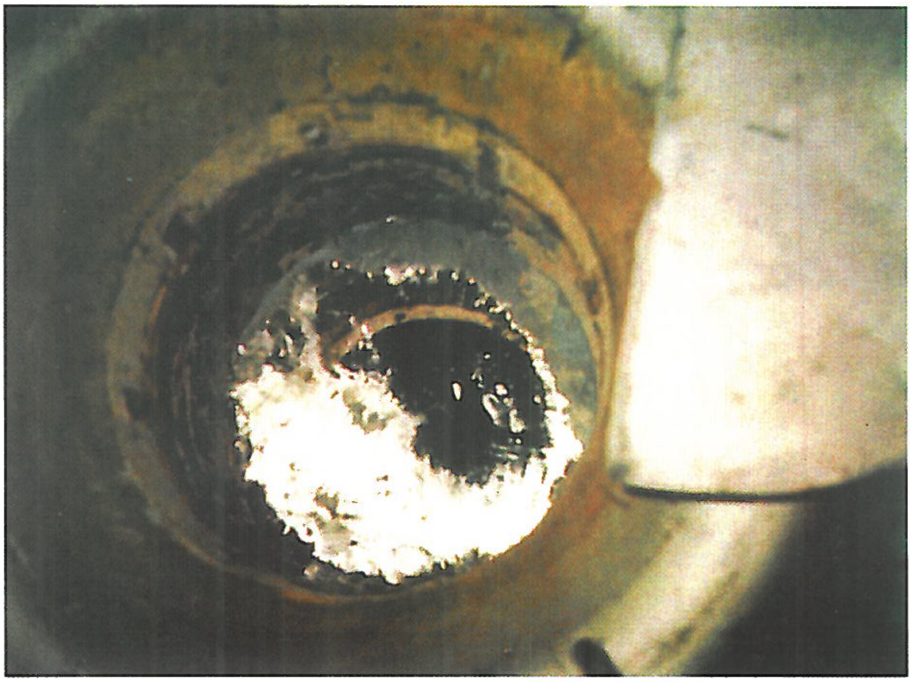


Fig. 42. The mirror surface of a particulates reinforced, aluminium matrix composite, illustrating the favourable effect of inert gas on the quality of composite (reduced content of oxides on the surface)

Fig. 43. When casting composites with a reinforcing phase susceptible to settlement or flotation it is possible to scoop up a portion of the liquid composite for further recycling even during the operation of mixing under the cover on inert gas

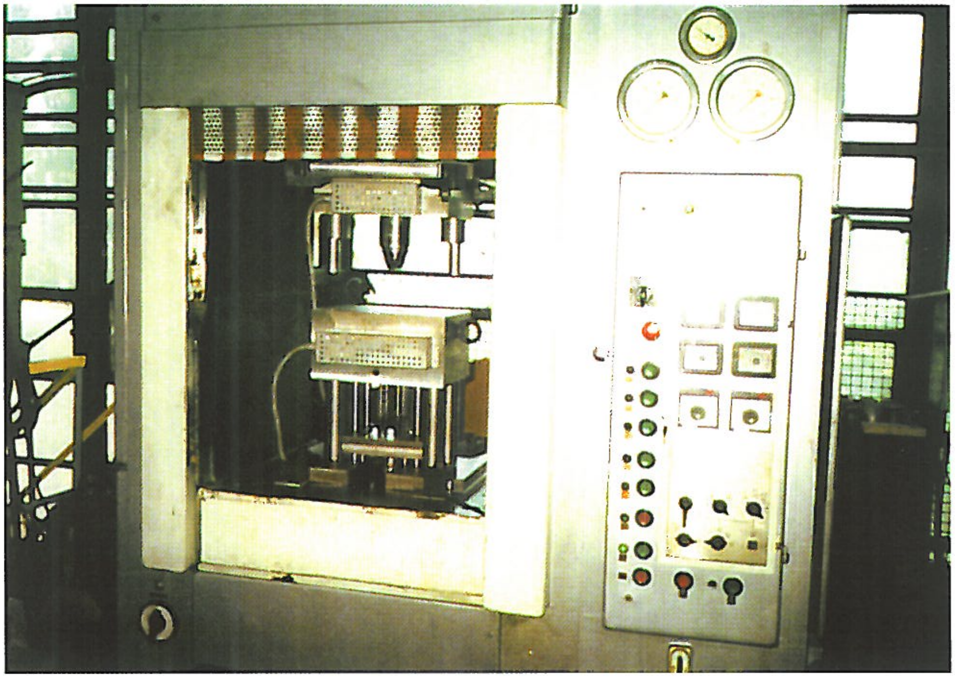


Fig. 44. A die for squeeze casting of composite pistons for I.C. engines, placed on the table of hydraulic press. On the right: a control desk for semi-automatic control of the solidification process under pressure. In front of the die there is a heating system

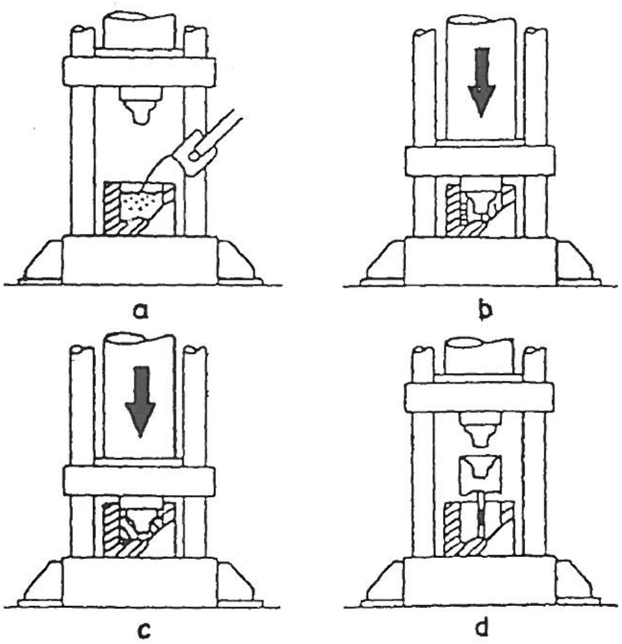


Fig. 45. Schematic illustration of different steps in a squeeze casting process: (a) pouring, (b) pressurization, (c) solidification, (d) ejection

Fig. 46. Application of protective and parting coatings on the working surfaces of a die for squeeze casting of composite pistons

Fig. 47. Pouring of the die cavity with liquid particulates reinforced composite. The four ends visible on the photograph are used for connecting the water or air feeding pipes to the cooling system

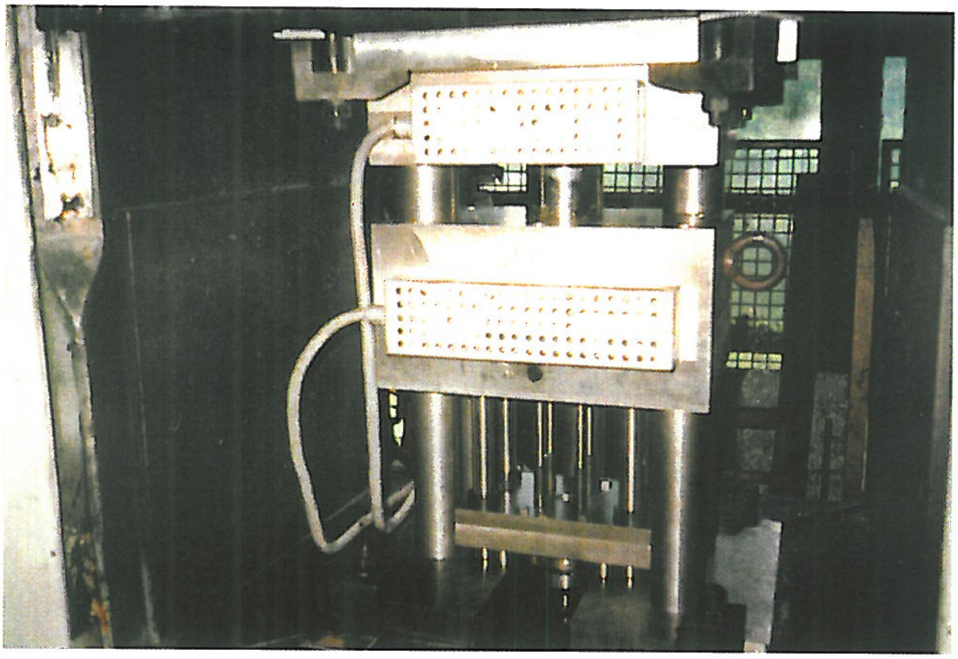


Fig. 48. Locking of die with simultaneous application of squeeze pressure onto the metal liquid. In most cases the pressure of over 100 MPa applied for a few tens of seconds is used

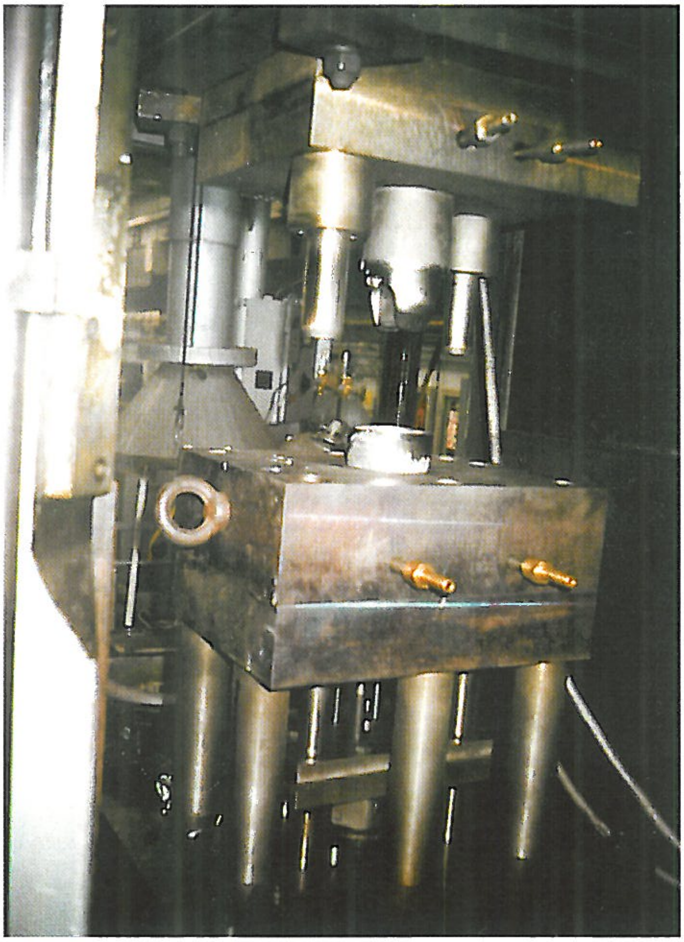


Fig. 49. Opening of die and ejection of the ready composite casting by means of ejectors system

Fig. 50. The ejection of a ready squeeze composite casting from the die

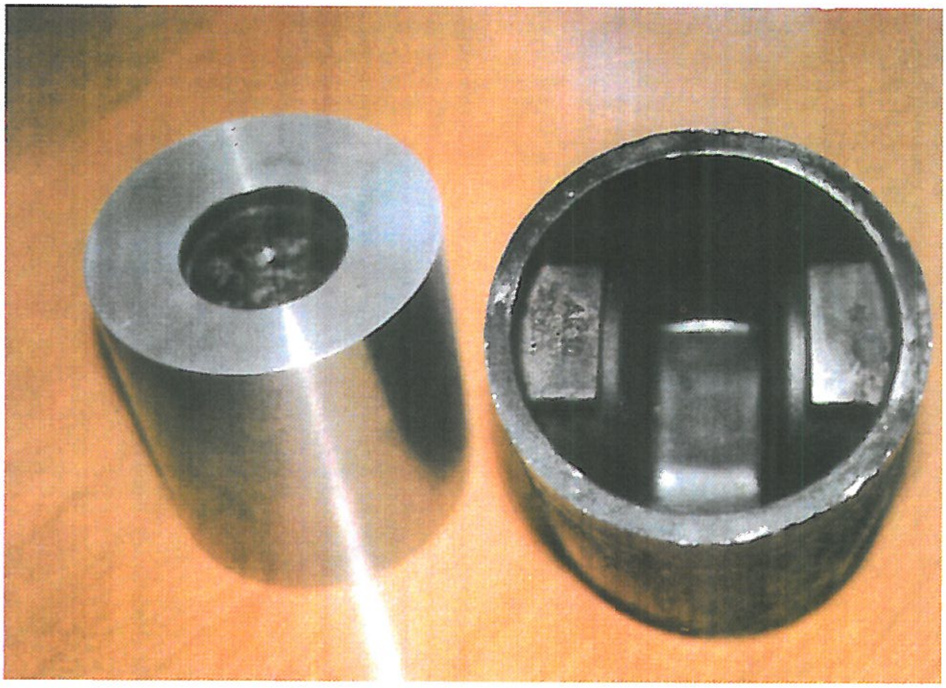


Fig. 51. Squeeze cast pistons made of the particulates reinforced Al–Si aluminium matrix composite

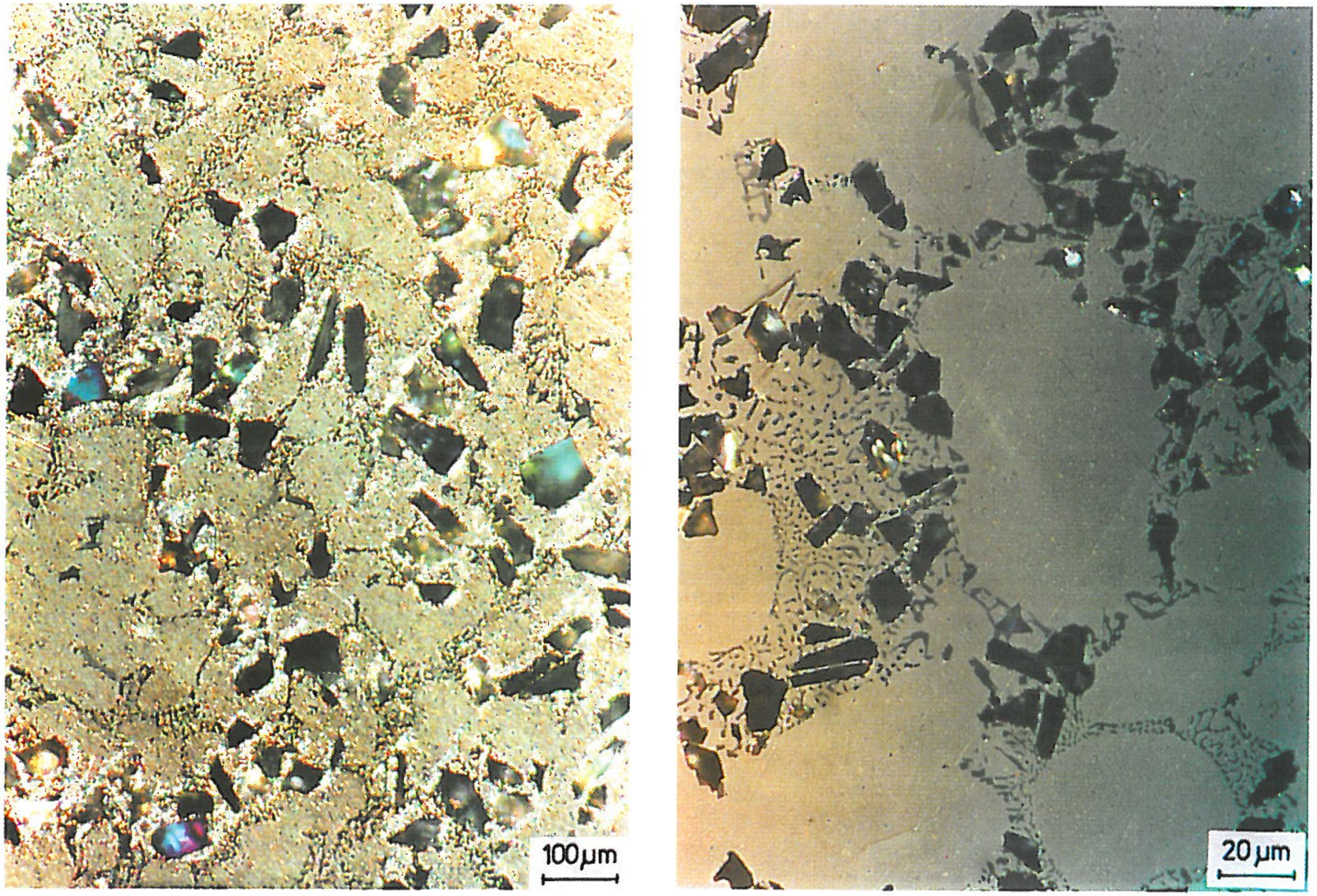
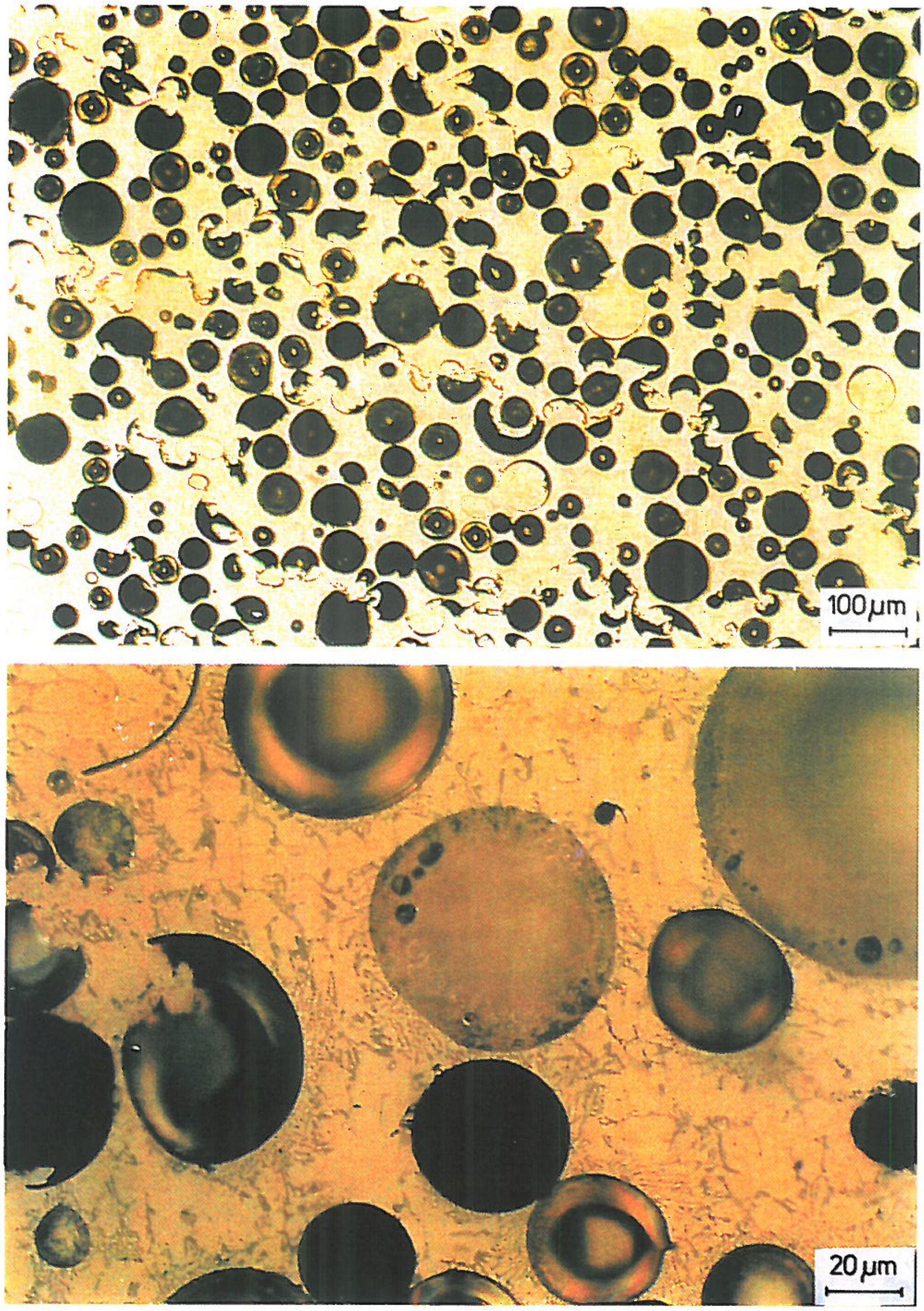


Fig. 52. The structure of A356+20 vol.% SiC squeeze cast composite (Foundry Research Institute, Kraków)



Rys. 54. Microstructure of aluminium alloy – cenosphere composite obtained by squeeze casting in the Foundry Research Institute, Kraków

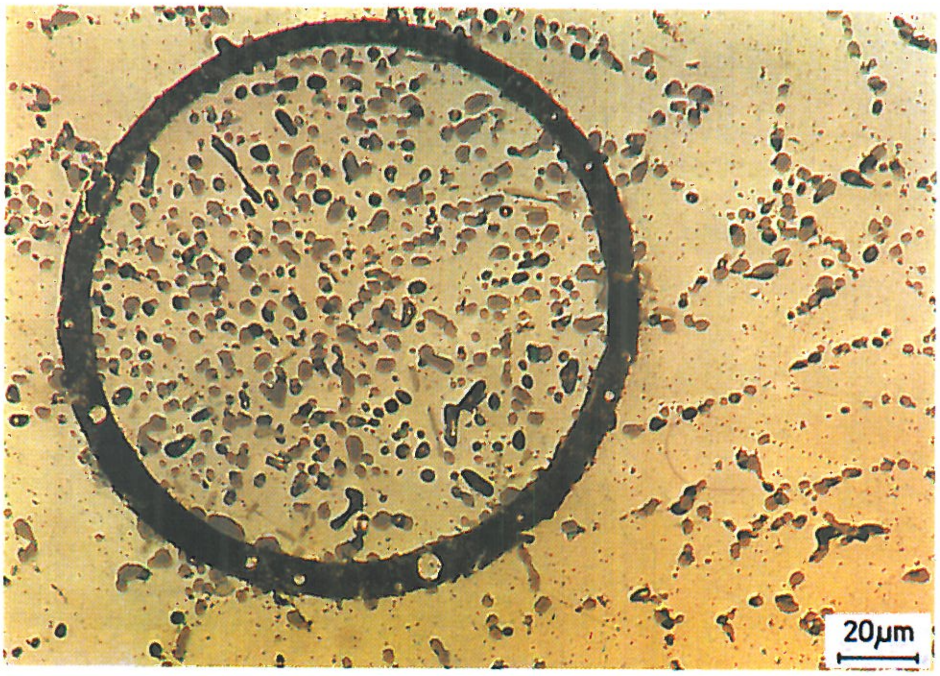


Fig. 55. During the solidification under pressure of a particulates reinforced Al7Si+2.5 wt % flyash composite, inside the particles of the reinforcing phase one can see the regions of where the metal matrix has a high degree of the grain refinement. The composite after heat treatment (type T6)

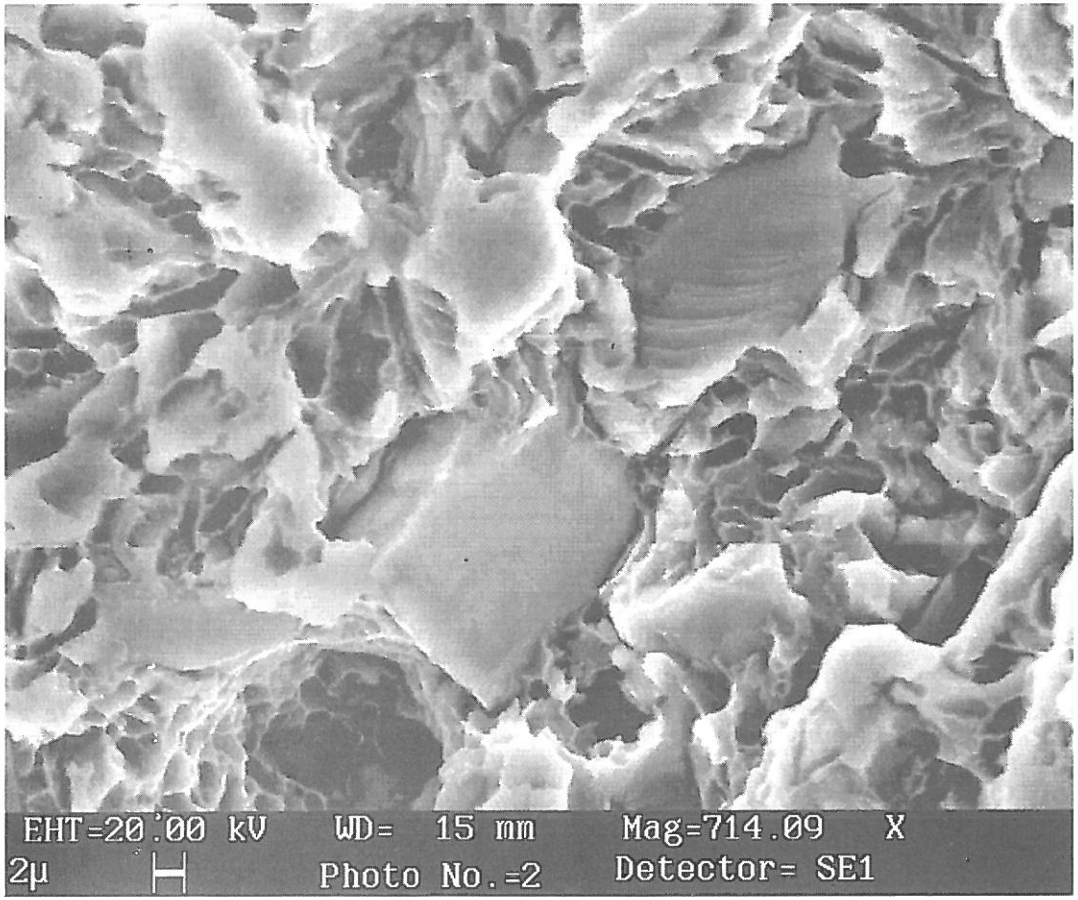
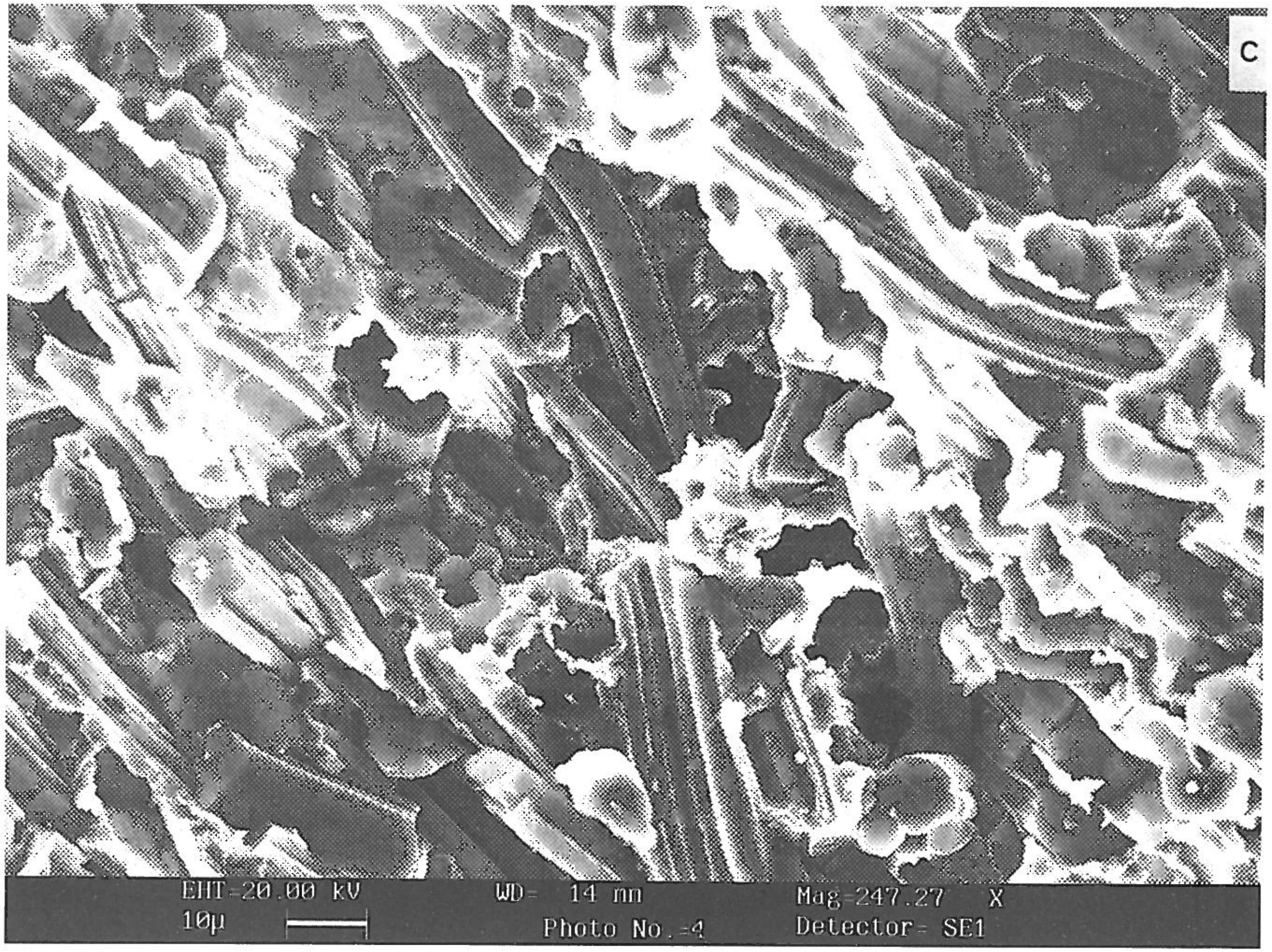


Fig. 56. Fracture of composite A354+20 vol.% SiC after squeeze casting (SEM). Foundry Research Institute, Kraków

Fig. 57. Microstucture of aluminium alloy – Polish carbon felt composite obtained by squeeze casting in the Foundry Research Institute (a), structure of fibre preform (graphite felt) (b), and fracture of AlSi12CuMgNi+ + graphite felt composite (c) made by squeeze casting in the Foundry Research Institute, Kraków


b
EHT=20.00 kV
20µ
WD= 12 mm
Photo No.=5
Mag= 61.82 X
Detector= SE1


c
EHT=20.00 kV
WD= 14 mm
Mag=247.27 X
10µ
Photo No.=4
Detector= SE1

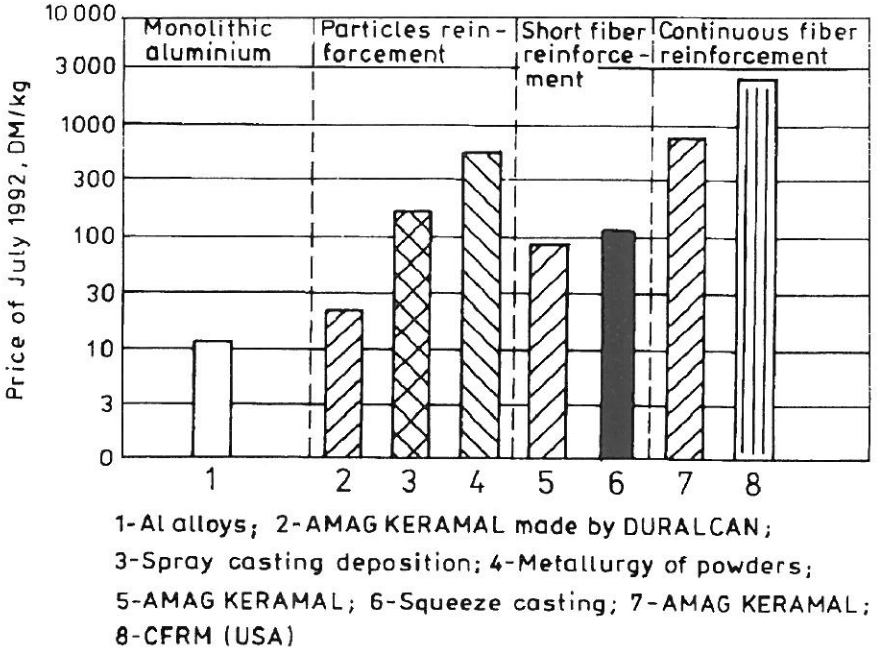


Fig. 58. A comparison of prices of one kilogram of the Al–based MMCs fabricated by different methods (from the data compiled by AMAG–FORSCHUNGS– und ENTWICKLUNGS G.m.b.H). The process of products made from DURALCAN pigs by AMAG (Keramal) and the prices of composite materials (aluminium matrix, continuous fiber reinforcement) made by CFRM (USA). The process of spray casting, also called osprey, is a method of making composites; the principles of this technology place it somewhere between the liquid phase processing and the metallurgy of powders

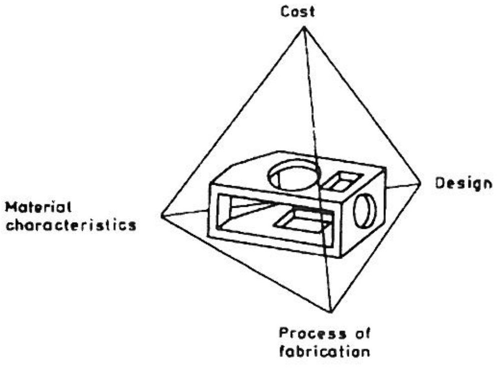


Fig. 59. Squeeze cast composite casting in optimum characteristics diagram

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Note: We would like to apologize that both in the text, tables and figures the word "fibre" is written either fibre or fiber.