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DEVELOPMENT OF Al MMC COMPOSITES FOR AUTOMOTIVE INDUSTRY[1]

RAZVOJ KOMPOZITA NA OSNOVI ALUMINIJA ZA AUTOMOBILSKU INDUSTRIJU

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ABSTRACT

The prospects of metal matrix composite (MMC) technology and its noteworthy application in the automotive industry is reviewed. Some examples of MMC products commercialized in Japan, USA and Europe are introduced and the reasons for their success analyzed. The motivation for the employment of MMC components in the automotive sector is based on the requirement for weight reduction and the pursuit of high efficiency in engines. The factors influencing the conventional and advanced forming routes for MMCs are listed. Finally, the cost-to-quality ratio evaluation of MMCs is also performed in order to predict the further commercialization of these promising materials.

Key words:Aluminum-based composites discontinuously reinforced with ceramic particles, examples of automotive application

REZIME

U radu je prikazan pregled najnovijih tehnoloških dostignuća na području kompozita na osnovi aluminija diskontinuirano ojačanih sa keramičkom fazom, sa naglaskom na njihovoj sve većoj upotrebi u automobilski industriji. Opisani su primeri uspešne komercijalizacije ovih materijala u Japanu, Sjedinjenim Američkim Državama i Evropi i analizirani faktori koji su doveli do njihove poslovne realizacije na tržištu. Osnovni motiv za upotrebu ovakvih kompozita u automobilkoj industriji je smanjenje težine vozila kao i u povećana efikasnost motora. Opisane su neke klasične i savremene metode strojne obrade ovih materijala i opredeljen je njihov uticaj na cenu automobilskih delova. Analiza odnosa izmedju cene i poboljšane kvalitete

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automobilskih delova izradjenih iz komopozita je bila osnova za ocenu dalje uspešne komercijalizacije ovih materiajala.

Ključne reči: kompoziti na osnovi aluminija diskontinuirano ojačani sa keramičkom fazom, primeri upotrebe

INTRODUCTION

The development of metal matrix composites has been one of the major innovations in materials in the past 25 years. Particle reinforced light metals are already attracting the attention of materials producers and end users because of their outstanding mechanical and physical properties. A major goal in manufacturing and utilizing MMCs, as will be discussed in detail later, is to achieve the highest possible strength to weight and stiffness to weight ratios in a low cost light material. Most of the published work has considered Al-based composites, with their attractions of low density, wide alloy range, heat treatment capability, and processing flexibility.

The principal attractions for the use of MMCs in the automotive industry can be summarized as follows: reduction in mass, especially in engine parts, improved wear resistance or lubrication characteristics, improved material properties, particularly stiffness and strength, providing either increased component durability or permitting more extreme service conditions, reduced thermal expansion coefficient.

Main drawbacks centers are: reduced ductility and toughness, extra cost of reinforcement over aluminum alloys, lack of design data, need to improve low cost, high volume, secondary processing techniques and doubts over recyclability.

2. DEVELOPMENT OF AL BASED COMPOSITES

Considerable development has occurred recently in the synthesis of discontinuously reinforced metal matrix composites (DR MMCs) with tailored properties. However, the high cost of current MMCs compared to aluminum alloys hamper the production on a large industrial scale, especially in the automotive industry. The stated goal of current investigations in the field of DR MMCs are to identify opportunities for research and development which will significantly reduce the cost of DR MMCs in automotive applications. Thus, the real objective of market oriented investigations in this field is to see if DR MMCs could be made affordable for use in the family automobile, and a key step in achieving this objective is to define what car makers are willing to pay for the improved performance of automotive components made by DR MMCs.

According to [1] there are two potential solutions for improving the quality and the economy of castable DR-MMCs: (1) creation of new casting techniques to reduce casting defects and disperse fine ceramic particles in a melt, and (2) development of new ceramic reinforcements with superior characteristics, such as spontaneous wetting and chemical stability in the melt.

DR MMCs can be produced by powder metallurgy [2], molten metal methods [3] including mixing methods [4], low pressure infiltration [4], high pressure infiltration - so-called squeeze casting[4,5], pressureless infiltration [6], spray deposition [7], the XD™ process[8] and others. Recently, Ejjiofor and Reddy [9] published an extensive review of these techniques.

Following main problems must be solved to facilitate the expanding application of DR MMCs in the transportation industry:

(1) Superior cost performances. In aluminum-based DR MMCs, the quality-to-cost ratio should be more than 1 (values of 1.3-1.5 are highly recommended). DR-MMCs should become a class of highly profitable materials with at least 30-50% of added value.

(2) Active implementation of environmental concerns. DR-MMCs should be easily recyclable or, at least, reclaimable materials.

(3) Improved ductility. The ductility of the composite should be approximately the same as that of the unreinforced matrix.

The immediate solution of these problems is impossible. However, many researchers and managers firmly believe that solutions will be found if the same amount of energy is devoted to solving these problems as has been expended during the past two decades of DR-MMCs R&D.

It is too soon to predict what the perfect solution will be, but DR-MMCs should be defect-free, castable and recastable. In this way, the most inexpensive processes for the production of final components will be established.

The cost-effective preparation of a dispersion with at least 20 vol% of fine ceramic particles produced *in situ* or introduced directly into a melt becomes the most important technological requirement. The three main questions are:

(1) How to improve the wetting behavior between ceramic particles and molten Al alloys to make their immersion easier and cost effective?

(2) How to stabilize fine ceramic dispersoids and to prevent their agglomeration, settling and rejection after successful immersion?

(3) How to improve the fluidity of dispersions of small ceramic particles. Sufficient fluidity is required to enable ingot casting directly from the

composite processing reactor. Casting fluidity after remelting of composite billets is necessary for secondary shape casting of composite parts?

These are fundamental questions, and the answers will be found through seeking new knowledge of wetting, surface engineering and interfacial chemistry. It is speculated [10] that the wetting of ceramic particles by molten metal could be improved by introducing exothermic interface reactions that provide sufficient energy for the wetting activation. Some progress has been made in the Al-SiC system [11]. However, the effectiveness of the solution offered remains about the same as that for the existing commercial foundry procedures that operate with 10-20 μm sized particles.

Improvement in fluidity could probably be achieved using new alloying elements or additives or by increasing the melt temperature. Increasing the working temperature could also enhance the wetting tendency between particles and melt, but, unfortunately, at the same time, also the reactivity between particles and molten alloy.

However, it seems that the type and the shape (aspect ratio) of discontinuous reinforcements are not dominant in further improvement of the mechanical properties of DR-MMCs, but mostly in the size and volume fraction of successfully incorporated particles in a melt.

This indication, which should be very carefully studied in future R&D efforts, may offer new opportunities for low cost fillers that are less expensive than the matrix. These fillers include some waste by-products such as fly ash [4], and also some fine aluminum dross particles [12].

3. ECONOMIC EVALUATIONS

The cost of a composite material, C, can be estimated by the following formula:

$$C= X_1C_1+X_2C_2+C_3 \tag{1}$$

where X_1 is the weight fraction of matrix alloy and X_2 is the weight fraction of the reinforcement in the composite, C_1 is the cost of matrix alloy, C_2 is the cost of ceramic reinforcement and C_3 is the production cost.

For a composite prepared using low cost pressed drained aluminum alloy and the cyclone fraction of dross particles one can take the cost of the matrix alloy as ~1.4 $/kg (this is the average commercial value of pressed drained aluminum), the cost of the cyclone fraction of dross particles as ~0.06 $/kg, and the production cost as the cost of squeeze casting or gas pressure infiltration which is typically less than 1$/kg (for medium size production).

Taking into account that $X_1 \approx X_2 = 0.5$ one can estimate the target price of the composite as less than 2$/kg which is slightly higher than the cost of non-reinforced aluminum alloy. Note that in the case of squeeze cast components the production cost is almost the same for non-reinforced and reinforced aluminum alloy. Further promotion of this concept must be on a value-added basis, i.e., on the improvement of the cost-to-quality ratio. On the other hand, there must be a market demand for improved properties before consumers will agree to pay for them. The automotive market-the largest potential market for MMCs-is traditionally interested in low cost articles with improved performance, and this is the significant promise for the fabrication of cast products from aluminum-dross reinforced composites. Of course, if the final consumers consider price alone, there will be little incentive for developing innovative solutions.

4. INCREASED PERFORMANCE PRICE

The entire DR-MMCs business philosophy is based on a value-added product. In other words, the introduction of a carefully selected ceramic reinforcement into a light-alloy matrix should result in a profitable material. Target prices for the increased performance of DR-MMCs have been established for several market segments. The automotive market-the largest potential market for DR-MMCs-is traditionally interested in low-cost improved performance.

The problem is that none of the available DR-MMCs production technologies can meet these requirements. The competition for various DR-MMC production methods has been identified. All potential production methods are operated in a no-value added region. However, because of their low production cost, foundry methods have the largest potential for a value-added product. The problem is how to meet the market specifications at the same target price, i.e. how to improve the quality of castable DR-MMCs within the required cost.

5. AUTOMOTIVE APPLICATION OF MMCS

In the automotive market, MMCs are used in the form of extruded and draw tubing to produce stiffer and lighter driveshafts. MMC driveshafts have higher critical rotational speeds for a given geometry, and operate at reduced vibrational noise levels. Other automotive applications include extruded stabilizer bars, forged suspension and transmission components and rolled/forged snow tyre studs. All of these applications benefit from either the increased stiffness or increased wear resistance attributable to an MMC.

On the other hand, many attempts to replace cast iron in automotive parts with aluminum alloys have been ongoing since the 1960's. As with most soft metals, aluminum suffers from poor resistance to adhesive wear or galling when in relative motion with another metallic or non-metallic surface. Several solutions to this problem have been proposed, including composite materials containing either silicon carbide, alumina or graphite in particulate form [4]. The possibility of substituting aluminum for cast iron provides the potential for a considerable weight saving as typically 12 % of the weight of a small economy car (about 100 kg in total) and 15-17 % of the weight of a diesel truck consists of cast iron.

The Toyota Motor Company /Art Metal diesel piston first announced in 1983 represents the celebrated first commercial automotive application of MMCs. The component was developed to reduce the weight of pistons and to improve wear properties by using a composite instead of cast iron around the piston ring grove. In addition, improved material properties permit the use of an advanced engine design with increased cylinder pressure and resultant higher performance. Such increased cylinder pressures lead to higher thermal and mechanical loads that must be withstood. Cylinder bores can be designed with a closer fit by using lower thermal expansion coefficient MMCs, thus permitting new piston designs with improved heat flow characteristics and reduced weight.

The inserts are produced by squeeze casting into alumina preforms; current production in is excess of more than 100 000 per month. Direct cost savings are the reason for the application of the aluminum composite insert, with increased wear resistance and weight savings as significant side benefits.

Automotive applications for MMCs are the subject of enormous development efforts in Japan.

The Honda connecting rod is reported to have produced a 30 % weight reduction with savings in fuel economy and improvement in engine power. Whereas the Toyota piston is produced with no extra cost compared to the original piston, the Honda connecting rod has cost four to five times that of the original forged steel component. The connecting rod development at Honda appears mainly to have been aimed at gaining experience in MMC processing.

At this stage, in view of current reinforcement costs, many of the developments described in this work are best considered as demonstration projects. While technical benefits can be readily achieved, substitution has not been considered sufficiently cost effective for introduction into routine production.

The question therefore arises as to why MMCs are considered to be so important by the Japanese - both government and industry. One of the reasons is strong competition between MMC reinforcement suppliers in Japan. In addition, there are economic pressures to diversify interests and a national enthusiasm for advanced materials development, backed up by an average of 3% sales invested in research, particularly for long term projects where no obvious market is foreseeable.

In 1989, new MMC technology was applied to a petrol engine cylinder block. Honda introduced engines using the technology in the United States and Japan. The cylinder block was made from aluminum and aluminum-based MMCs. Weight was reduced by 20% over previous aluminum engines, and the cylinder block weighs only half of one made from cast iron. It was reported [13] that an MMC layer is formed inside the cylinder by appropriate technology. The MMC layer has adequate durability to withstand the high speed sliding conditions and high temperature of the piston rings. This MMC layer is reinforced by hybrid fibres, which are a combination of alumina and carbon short fibres, providing the necessary strength and sliding characteristics. The MMC layer has a thickness of 2.0 mm, with a reinforcing short fibre volume ratio of between 12-15 %. In addition to superior sliding durability, cylinder-cooling efficiency was increased due to the high thermal conductivity, helping to improve engine characteristics. Since Honda engines equipped with this MMC technology were introduced, over 300 000 have been produced. They have been especially popular for their superior performance and revolving response characteristics.

Another commercial MMC application is in a crank damper to achieve component vibration damping. This technology was implemented by Toyota in 1991. Optimum damping and a decrease in weight were achieved by providing a partial MMC application to the aluminum alloy for the damper hub designed to attenuate crank torsional vibration. This MMC portion is reinforced with a 10% volume ratio of short alumina silica fibre, providing high compressive creep strength and adequate machining characteristics. Weight was reduced by approximately 20 % over a steel pulley.

In 1993 Honda introduced new technology based on MMCs for the production of cylinder liners in high rpm, high power motorcycle engines. To produce this cylinder liner, a composite billet is made by mixing 17Si alloy made using the rapid quenching method (10^2 to 10^3 K/s) with 3-5 % fine alumina powder and 0.5 to 3 % graphite powder. The pipe-shaped aluminum alloy composite is made from the billet by means of cold static press and extrusion processes. This material has superior resistance to heat and wear, and can be directly cast into during the cylinder block casting process. This achieves excellent adhesion with the block, enhancing thermal conductance, with a corresponding improvement in engine combustion and increased power output [13].

In the USA, Clemite have undertaken a programme to develop alumino silicate fibre reinforced diesel pistons, the reinforcements being applied in the crown and ring groove areas. Zoeller Pistons are assessing squeeze casting for fibre-reinforced materials for their products. Technically these have proved very successful but at this stage they are not cost effective.

However, it is necessary to stress that several US large national programs focused on MMC development and applications in aerospace and the military sector have been successfully performed in past. The accumulated data concerning some actual and near future planned consumption of these materials in aerospace and military applications are, of course, highly classified. Based on some available information [14] it is evident that Hughes Aerospace and Electronics Co., General Motors, National Automotive Center and Advanced Refractory Technologies Inc. in the capacity of the metal matrix composites Implementation Working Group of the North American Defense Industry Base Organization (NADIBO) completed, for example in 1994, a very detailed investigation of MMCs for advanced military applications, especially for tank parts and missile structures. The group has adapted a new squeeze casting approach for moulding MMCs using newly developed low-cost SiC whiskers produced by Advanced Refractory Technologies Inc, NY. The partners demonstrated that not only does this process produce a near net shape part at much lower cost, but, through the clever application of preform fabrication technology, the parts can be selectively reinforced where needed, with the remainder of the casting having base aluminum properties.

Inco Ltd., the Canadian company recently developed a new aluminum based MMC containing nickel coated graphite particles in combination with silicon carbide particles for cast cylinder liners, cast rotors and disc brake systems. As reported by the producer[4], the excellent wear behaviour is provided by a combination of solid lubrication by graphite as well as high temperature strengthening of the matrix alloy by nickel present as Al_3Ni precipitates.

In Europe, the majority of work undertaken is still at the development stage. Some exceptions are discussed below.

Automotive Engineering (UK) are reported in 1990s to be capable of producing pistons reinforced with ICI Saffil alumina fibre. Pechine (France), Daimler Benz (Germany) and Fiat (Italy) were also worked along similar lines. In the UK in the early 1990s, Cray Advanced Materials was studying fibre-reinforced metals for brake discs, connecting rods, etc. Alcan has also looked in the past at connecting rods, to lower the reciprocating mass. ICI PLC, VW AG, Agusta SpA, VAW Aluminium AG in 1990-93 through the Brite-Euram project investigatedthe development of novel automotive piston/rod components and aerospace gearboxes from long fibre metal matrix composites.

In another Brite-Euram project, a consortium consisting of Aerospatiale, Alusuisse, Raufoss and Deutche Aerospace AG have developed the necessary technological basis for the production of sheets and sheet structures from particulate reinforced MMCs. Deutsche Aerospace AG, Aerospatiale, British Aerospace, Alcan International, Pechiney, Otto Fuchs Metallwerke, INSA and LNETI also investigated low cost MMCs made by spray deposition through the Brite-Euram project performed in 1990-93. Brake drums, brake discs, beraing cups, suspension arms and some aeronautical parts produced by MMC forging was investigated in the 1990-93 Brite-Euram project (BE-5229) performed by Riso, Alcan International, Stampal, SpA, BSF, Centro Ricerche Fiat and several European universities. It was found that the mechanical characteristics which have been reached can allow the replacement of items produced at present in iron and steel, making the most of the 1 to3 average ratio of the specific weights, with evident weight reduction benefits. For this reason FIAT, Renault, Ferrari, Lamborghini, Audi, Aliena, Agusta and Aerospatiale are interested in further development of this technology. Brake components in MMC will probably be part of a new model "Punto". Casting will produce the parts, since the fabrication procedure with extruded stock and forging and machining is too expensive. The Barchetta (new model) may use such brake components with a production 90 000 cars/year corresponding to 180 000 discs/year on the rear wheels. Bravo/Brava models with a production of 1.8 million drums/year are also potential models to be equipped with such brake components. Weight savings are about 50% for brake drums and 60% for brake discs, corresponding to about 3 kg per piece. Bearing caps need further testing but could be introduced in 1997-98; MMC weight saving is about 30%. Suspension arms may be used in high-performance cars like the Ferrari in 1998, since it is too expensive for cheaper cars; weight saving is about 40%.

Note that a fairly long list of very strong R&D activities in the field of the automotive application of MMCs, which is being performed at European non-profit making institutions (universities and institutes) is excluded from this report. These data are available on CORDIS WWW pages and demonstrate how much academic work is necessary to complete before the risk of industrial projects becomes acceptably low.

At the leading edge in forming of aluminum-based materials, Stampal SpA from Torino is particularly involved in encouraging the opening of new frontiers and market opportunities for these materials in Europe and abroad. As one of the European leaders in this field, Stampal SpA has participated in several Brite-Euram project deals with MMC for automotive applications. Recently, Stampal SpA and Impol, the leading Slovene producer of aluminum alloys and finished parts, signed a joint-venture agreement, which particularly includes R&D and business activities in the forming of aluminum-based materials for the automotive industry.

6. COST-EFFECTIVE AL MMC FORMING METHODS

Considering that aluminum-based composites contain hard ceramic particles, have high wear resistance and limited ductility, even the most straightforward operation, such as sawing, can require modification of conventional equipment. Extensive sawing and machining studies have been carried out, and viable commercial practices established [15].

Most applications require some degree of machining, such as sawing, milling, drilling, reaming, and tapping. The ceramic particles present in composites have a hardness approaching that of the machine tool material, which means that abrasive wear of the tooling is the main issue. To minimize abrasive wear the area and contact time between the tool and the work-piece should be kept as low as possible. This means that MMCs should be machined at higher feed rates and depth of cut than traditionally used with unreinforced Al alloys.

The hardness of the tooling is an important factor in controlling tool life. High-speed steel tools are dulled in seconds, while conventional and coated carbide tooling lasts only a few minutes. By far the most cost effective tooling is polycrystalline diamond (PCS), provided it is of high quality. Unfortunately, PCS tooling is not yet available for taps or very small diameter drills and reamers, especially at a reasonable price, so carbide tools must be used for these operations.

The automakers, through a combination of supplier collaborations and cooperative research projects, are aggressively addressing the development of new technologies that can reduce primary material feed-stock costs. The manufacturing methods needed to process and form aluminum based composites in a reliable repeatable manner - while minimizing scrap, assembly operations, and joining steps-remains an area of great research need. One of the most important application areas for lightweight materials is the use of aluminum-based materials in car body structures. In the case of aluminum-based composites, stamping process modeling and more sophisticated material models are needed to allow accurate forming predictions and improve the repeatability of the process [16].

In addition to aluminum-based material stamping, a number of emerging forming and manufacturing methods for light metals and composites were recently suggested by different project teams. A partial list of advanced forming techniques that are particularly applicable to aluminum-based composites for automotive applications include hydroforming, electromagnetic forming, super-plastic forming, extrusion and extrusion shaping, and semi-solid forming or moulding [16]. As recently discussed by Smith and McVay from Pacific Northwest National Laboratory [16], each of these forming technologies offers attractive advantages as well as significant limitations to their use in higher-volume, cost-driven applications. A particularly difficult aspect of many of the new forming technologies is that suppliers will need to become the experts in these technical areas. To be successful, this will require that suppliers develop the modelling and simulation capabilities that will allow them to design and optimize the forming process with a minimum of empirical development.

7. SUMMARY

This article highlights some of the new and exciting aluminum-based composite processing and manufacturing technologies, which are emerging for automotive applications. Examples of MMCs products successfully applied in the automotive industry were listed. The cause of success was analyzed and discussed to promote the application. Although the list is far from complete, it includes a number of the most important examples that have potential to reduce further the cost of manufacturing high-performance, lightweight automotive components and structures and accelerate the consumption of MMCs in the automotive segment.

The advancement of MMCs in the automotive market is still hampered by the current low volume usage of these materials, mostly caused by their high cost in comparison with the aluminum matrix and, in some cases, by the lack of theoretically predicted properties. As these materials reach maturity, many significant challenges must be met as this technology is scaled-up for automotive component fabrication. The successful commercialization of metal matrix composites will finally depend on their cost effectiveness for different applications. This requires optimum methods of processing, machining, and recycling, including some very new and advanced forming routes.

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