PROGRESS ON THE DEVELOPMENT OF ALUMINIUM METAL MATRIX COMPOSITE AS AN ALTERNATIVE PISTON MATERIAL- A REVIEW

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Abstract: The decision of material selection in the various engine components of the automotive industry is highly complex and ever challenging due to the utmost concern related to the fuel economy, improved safety, global warming and energy usage. Aluminium castings have been traditionally used for almost 100% of pistons in petrol and diesel engines. However, one of the most significant drawbacks of aluminium alloys is that they demonstrate low wear resistance. Despite of its widespread use in automotive applications, Aluminium alloys perform poorly at high temperature applications. To overcome some of the limitations associated with the alloys, development of metal matrix composites are getting growing interest amongst the researchers. However, limitations associated with the manufacturing costs as well as the inherent casting defects of such composite piston hindered the future research on the development of AMMC based piston materials. This review focuses on the recent development of AMMC piston material, associated fabrication methods as well as future prospects of research on the AMMC piston materials.
Index Terms- **AMMC, tribological properties, mechanical properties, CNTs, Self- lubricating.**

I.INTRODUCTION

Piston is one of the critical tribopair in IC engine because it works under high temperature, high pressure, corrosive and multi-regime wear conditions. In an IC engine the piston's primary responsibility is to take thermal energy created by fuel-air combustion and transform it into linear motion. Modern pistons for internal combustion engines require highly specialized and cost effectively developed materials which should be characterized by low density, suitable thermal expansion and conductivity, resistance to thermal shock, good tribological properties, enhanced mechanical properties including fatigue strength, hardness and capability for vibration damping. In order to satisfy the fuel economy, light-weight materials such as aluminium–silicon alloys have found their place in most of the mass production of cylinder blocks, pistons and piston insert rings. Aluminium castings have been traditionally used for almost 100% of pistons in petrol and diesel engines. However, one of the most significant drawbacks of aluminium alloys is that they demonstrate low wear resistance. Despite of its widespread use in automotive applications, Al–Si alloys are not suitable for high temperature applications. Another major problem in aluminium piston is piston slap. It occurs due to high thermal expansion of the aluminium material as compared to its counterpart.

To overcome some of the limitations associated with the alloys, development of metal matrix composites are getting growing interest amongst the researchers. Aluminium metal matrix composites (AMMC) have a smaller rate of expansion than the aluminium and cast iron in which most pistons operate. Many attempts were made for the development of piston materials by reinforcing SiC, Al2O3, ZrO2, etc into the Al-matrix. The unique properties of AMMCs, especially designed for these applications offers an alternative to former materials and allow exceptional solutions for automotive engineering materials such as in brake rotors, pistons, connecting rods and MMC engine blocks. Large numbers of positive performances of AMMC piston from the previous few such instances of commercial pistons it implies that there is a huge scope of commercialization of AMMC pistons. Besides, from the decade long research it is also found that hybrid composites are far better than single particle reinforced MMCs in numerous aspects.

However, limitations associated with the manufacturing costs as well as the inherent casting defects of such composite piston hindered the future research on the development of AMMC based piston materials. In this context, it is worthwhile to mention that until and unless the extra manufacturing cost associated with the AMMC piston is not overshadowed by the high strength and performance of the developed materials, the sustainability of the designed material is of critical concern.

II. RESEARCH AND DEVELOPMENT ON AMMC AS AN ALTERNATIVE PISTON MATERIAL

Breakthrough in the area of aluminium MMC application was started in 1983 when Toyota car manufacturer produced high quality pistons with improved wear and fatigue resistance for diesel engines in mass scale. This was followed by the intense research by the scientists and engineers of Japan, Germany, China and UK to mass produce the ceramic fibre reinforced AlSi composite pistons and to attain the industrialization thereof. The following comprehensive review based on the national and international research and scientific works will present the state-of-art on the development of advance materials for automobile piston using AMMC, the adopted manufacturing techniques as well as the further scope of the research and development in the relevant field.

From the last few decades, a great deal of works has been carried out internationally in the field of AMMC to explore its potential automotive applications. A glimpse of such works can be found in some of the notable review articles of Allison et al.(1993), Chowla et al. (2006) and Macke et al. (2012). Elmarakbi (2013) authored a book on the advanced composites materials for automotive applications. Donomoto et al. (1983) developed a CF Reinforced AMMC piston for diesel engine. From their study, it was reported that the designed material performed well at elevated temperatures in terms of mechanical, thermal and tribological point of view. They recommended the use of AMMC for the strengthening and modification in the area of top land and top ring groove of piston to avoid the sacrificing of manufacturing cost and productivity. Hunt et al. (2001), provided a comprehensive review on the potential automotive applications AMMCs. Rudnik et al. (2003) illustrated the limitations which result from the materials and design of existing AMMC for pistons and other engine components to improvement of engine operation features. Dolata et al. (2007) for their investigation developed composite pistons of Al/SiC and SiC/C by mould casting and found that there is a heterophase reinforcement from utilization the technology of mould casting. Goni et al. (2013), suggested a new low cost metal matrix composite for pistons, clutch discs, and train brake discs.

The research on the AMMC piston material development in India is very limited and incomprehensive. Most of the Indian authors, presented some of the well-structured and concised review of the relevant researches that are being carried out worldwide on the prospect of AMMC in automotive applications (Prasad et al. (2004), Panwar et al. (2018), Moona et al. (2018), Vellingiri (2018)). A very few researchers focussed their works on the development and performance analysis of the AMMC piston materials. Krishnan et al. (1980) fabricated Al-Si-graphite particle composite alloy pistons by casting. From their preliminary finding it was concluded that Al-G composite is a promising material for automotive pistons. Karthe et al. (2016) made an attempt to develop the AMMC piston materials by adding the glass fiber to aluminium piston and found an improvement in the thermal and mechanical property of the piston. Additionally, a few preliminary and more simplified studies on the design and analysis of AMMC pistons were also carried out by some researchers (John et al. (2015), Singh et al. (2016)).

Al alloys used for the above studies mostly involved Al6061, 6063, 7075, A390, A356 as matrix material and Al2O3, SiC, ZrO2 as hard reinforcements. Now-a-days, carbon nanotubes reinforced MMCs (CNT-MMC) are being explored for automotive applications. Carbon nanotubes (Fig. 1) have proven ultrahigh strength and modulus (Umma et al. (2012), Song et al. (2011)).

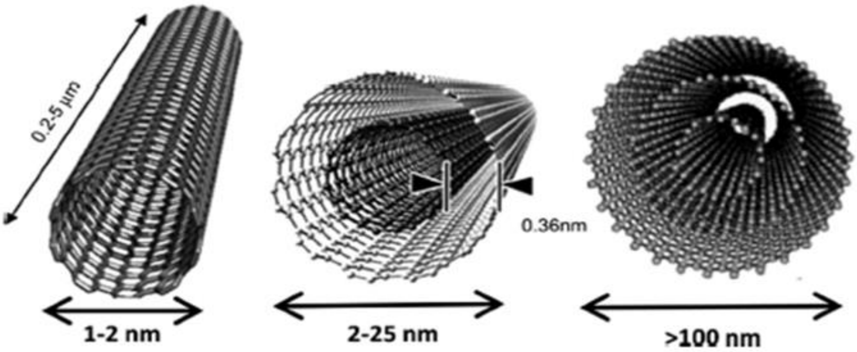

Fig. 1. Single, double, and multi-walled CNTs (Song et al. (2011)).

When CNT is reinforced in a metal matrix, they enhance the significant property of matrix such as superior mechanical, electrical, magnetic and tribological properties (Singla et al. (2015)). In 2015, Ali Alizadeh et al., in their work on hybrid composite (Al5083-CNT-B4C) found that addition of CNT in Al5083 reduce the wear resistance due the agglomeration of CNT but by the addition of B4C in Al5083+CNT become hybrid composite which increase the wear resistance. Highest wear resistance was found by addition 10vol% of B4C in Al-CNT composite (Fig. 2).

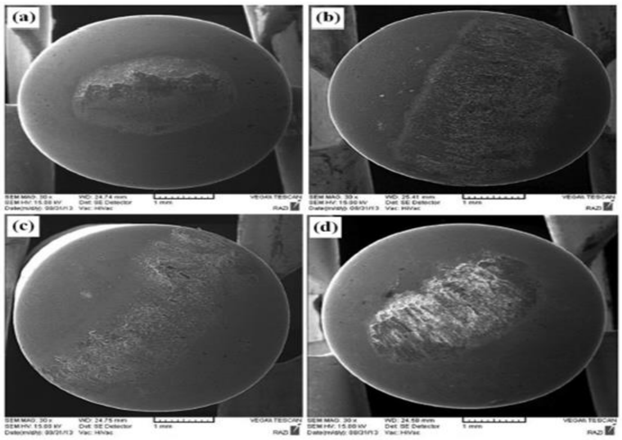

Fig. 2. SEM image of (a) Al, (b) Al-CNT, (c) Al-CNT-5 vol.%B4C, and (d) Al-CNT-10 vol.%B4C after wear test. (Ali et al. (2015))

Kwon et al. (2010) observed that addition of CNTs in aluminum alloy reduces the grain size and resulting in additional higher strength composite. Thus, based on a few more prospective studies directed towards piston material which are available in the literature (Kurita et al. (2011), Rael et al. (2016), Carvalho (2016), Zakaulla et al. (2018) and Duan et al. (2019)), CNT can be deemed as one of the potential candidates for self-lubricating and wear resistant piston materials.

III. RESEARCHAND DEVELOPMENTONTHE FUNCTIONALLY GRADED AMMC AS AN ALTERNATIVE PISTON MATERIAL

FGMs are a class of advanced composite that composed of continuous or discontinuous composition gradient. Functionally graded material (FGM) depicts compositional and microstructure gradient along its thickness or characteristic length and can be introduced to be a great solution to this problem. These materials can achieve differential functional behaviour since the property of one side of the FGMs can be differed from one side to the other side as per the application requirement. By controlling the property gradient, the product can be customized to meet any specific need within the best utilization of the composite components. Powder metallurgy, graded casting, laser cladding, thermal spraying are some of the methods that are being attempted till date to fabricate FGMs. There is a limited work available that has been carried out for the development and analysis of functionally gradient AMMC. Till now, centrifugal casting is regarded as one of the feasible and economic method to fabricate the functionally graded AMMCs (Velhinho et al., (2004)). Arsha et al. (2015) through their work designed and fabricated a FG-AMMC for automotive pistons using centrifugal casting of A390. Their results showed that centrifugally cast FGM pistons provide high hardness, thermal resistance and wear properties than that of conventionally gravity cast pistons.

IV. RESEARCH AND DEVELOPMENT ON THE FABRICATION TECHNIQUES OF AMMC

However, the currently used processes for the fabrication of the AMMCs are stir casting, powder metallurgy, conventional laser sintering, spark plasma sintering (SPS) and microwave sintering. But these mentioned processes have a lot of limitations which affects the efficiency and use of MMCs. The problems associated with different processes include porosity in powder metallurgy due to slow heating rate, thermal distortion of the material due to intense laser beam in laser sintering, only simple and symmetrical shapes can be manufactured with SPS. The most common and economical production route for composite fabrication is Powder Metallurgy (PM) and Casting. Depend upon the type of pressure and heat, PM's route can be sub divided in to four different methods Shown in Fig.3.

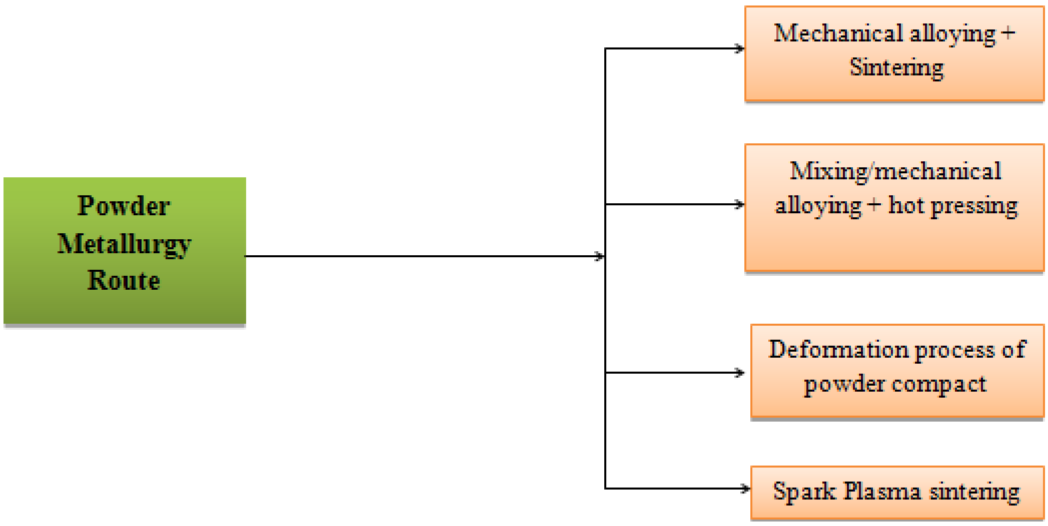

Fig. 3. Sub divisions of powder metallurgy route

As compared to the conventional casting, better dimensional and geometrical precision and good mechanical properties can be obtained by PM. Most of the works reported till last few years fabricated AMMC for their investigation using more conventional casting route, which has its inherent drawbacks. Besides, some disadvantageous associated with piston material development using traditional casting route includes ceramic particles' sedimentation, floatation or agglomeration (results in poor castability), poor solidification and crystallization, inferior mechanical properties, including reduced corrosion resistance of a composite. Hence, there is a need of an alternative manufacturing technique.

More recently, Falsafi et al. (2017) developed a lower cost AMMC automotive piston using 2124/SiC/25p. They investigated the mechanical and forging behaviour of AMMC developed by a lower cost processing route using powder metallurgy. They performed finite element modelling and analysis to examine forging of an automotive piston and die wear. However, to the author's best of knowledge, there is no work available on the high temperature tribological studies of the developed AMMC to assess their performance in the similar environment such as prevailed in IC engines.

Microwave sintering is a novel material processing technique, wherein the materials themselves absorb microwave energy and then transform it into heat within their bodies. It has many advantages like densification (reduced porosity), less processing time (higher heating rate) and uniform grain structure (volumetric heating), energy saving and cost effective. Using microwave processing the rate of yield can be highly enhanced. For AMMC the sintering temperature is 6000C which can achieve by microwave sintering in 30min with increment cycle of 250C/min (Matli et al. (2016), Ghasali et al. (2018)). However, in microwave sintering most metals reflect the microwave irradiation at room temperature (Singh et al. (2015), Shakoor et al. (2016)). These problems can be overcome by using the newly introduced MMC fabrication process i.e. sintering by Microwave hybrid heating (MHH), which uses the concept of hybrid or two directional heating Matli et al. (2016). Microwave material processing route has been extensively explored by some of the Indian researchers, especially for cladding and sintering (Gupta et al. (2012), Kaushal et al. (2017), Honnaiah et al (2018), Singh et al. (2018), Kaushal et al. (2018) . In 2012, Liu et al., made a successful attempt to fabricate W/Cu functionally graded composites materials by the use of Microwave sintering.

V. FUTURE PERSPECTIVE OF RESEARCH AND DEVELOPMENT IN AMMC AS PISTON MATERIAL

From the national and international status of works that has been presented in the earlier sections it is evident that it is of great demand indeed wherein, the scientists and engineers are coming together with a great zeal and enthusiasm in creating stronger lightweight materials by infusing different materials into Al alloys to increase the efficiency and performance. However, this has to be achieved with the reduced cost of production along with an environment-friendly and energy effective manufacturing technique. Amongst the family of aluminium alloy AlSi is proven to be the obvious choice of matrix material for IC engine piston. However, a very limited works can be found in the literature which is dealing with a comprehensive overall assessment of AlSi based composite materials developed as an alternative piston material. Moreover, it is worthwhile to mention in this context that the manufacturing cost of MMCs for the said purpose can be controlled by selecting an economically producible technique. Powder metallurgical route in combination with microwave material processing is one such green approach which can be time and cost saving as well as energy effective mean for piston material development.

Superior mechanical properties can be achieved for piston materials with suitably selected hard and thermally stabilized reinforcement phase(s) depicting the good bonding with the matrix. CNT-MMC and CF-MMCs are emerging out as a new class of material for such purposes on which research is still in the infancy stage.

Finally, to control the cost and enhance the performance the AMMC developed for piston is recommended to be functionally graded with reinforcing agents. Very few researchers and industrialists who had earlier developed AMMCs for piston materials focused on the functional gradation of the reinforcements in the developed piston to control the cost and acquire the best cost performance. Research on the development of functionally graded CNT or CF reinforced AMMC using the novel and much promising processing route of microwave sintering for the piston material development is the least explored area amongst the Indian scientists. Besides, there is no work found on the high temperature tribological studies of the developed AMMC to assess their performance in the similar environment such as prevailed in IC engines.

In short, looking at the potential application of suitably designed AMMC for the automotive piston, there is an ample scope of research for the development of a high performance, cost and energy effective novel AMMC for the IC engine components, especially for automotive pistons. The future developments should be targeted on manufacturing techniques with cost-energy effective, time saving features along with the enhanced desired properties. Moreover, a very few works till date has been reported on the development of piston materials and their detailed performance analysis. The high temperature tribological study using the developed FG-MMCs will help in understanding the mechanical and tribological degradation of these developed materials under elevated temperature, that usually prevail during the piston/cylinder liner contact in automobile.

This in turn, will help in developing the strategy of material development for challenging tribological applications such as at the elevated temperature, corrosive and sea water environment. The subsequent future works may open-up new dimensions of research in the field of FG-AMMC for their diverse applications such as in aerospace and structural applications

VI. CONCLUDING REMARKS

There is an ample scope of research gap still exists in the development of the piston material. With this motivation, attempts should be made for the development of a functionally graded novel AMMCs by using a novel material processing route which can be deemed as greener-cum-cost and energy effective manufacturing technique and which can yield the piston material with superior desirable properties. A comprehensive assessment of the properties of the developed materials and subsequent performance analysis of simulated pistons using the developed material is also required to be investigated. The outcomes of the future study can be fruitful in developing more environmentally benign, energy effective, low cost high performance materials for the various automotive engine components.

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