

Lower Cost Automotive Piston from 2124/SiC/25p Metal-Matrix Composite

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ABSTRACT

Engineered materials have made a breakthrough in a quest for materials with a combination of custom-made properties to suit particular applications. One of such materials is 2124/SiC/25p, a high-quality aerospace grade aluminium alloy reinforced with ultrafine particles of silicon carbide, manufactured by a powder metallurgy route. This aluminium matrix composite offers a combination of greater fatigue strength at elevated temperatures, lower thermal expansion and greater wear resistance in comparison with conventionally used piston materials. The microscale particulate reinforcement also offers good formability and machinability. Despite the benefits, the higher manufacturing cost often limits their usage in high-volume industries such as automotive where such materials could significantly improve the engine performance. This paper presents mechanical and forging data for a lower cost processing route for metal matrix composites. Finite element modelling and analysis were used to examine forging of an automotive piston and die wear. This showed that selection of the forging route is important to maximise die life. Mechanical testing of the forged material showed a minimal reduction in fatigue properties at the piston operating temperature.

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INTRODUCTION

Metal-Matrix Composites (MMC) offer attractive features to automotive engineers and designers to meet the current and future challenges for improved performance, fuel-efficient, and low-emission vehicles. Properties of these materials can be tailored to meet specific design requirements of various powertrain or chassis components. Compared to conventional materials MMCs provide a high strength-to-weight ratio, enhanced mechanical and thermal characteristics, improved fatigue and fracture properties, as well as excellent wear resistance [1]. Metal matrix composites are mainly used to produce engineering components for aerospace and electronics industry or custom products for racing cars. Applications in the automotive sector are limited to a few engine components such as drive shafts or brake components. Since the automotive industry is a highly cost-sensitive sector thus the high cost of composites and required infrastructures restricts the application of these materials [2].

One of the advanced materials to replace conventional structural alloys is a high-grade aluminium alloy AA2124 reinforced with ultrafine particles of silicon carbide. Its high strength, fatigue resistance and hardness at elevated temperatures make this composite a successful candidate for automotive engine components such as valve train, pistons, cylinder liners or connecting rods [3], [4]. Properties of this composite such as strain hardening at different temperatures are reported in [5] while the behaviour under monotonic and cyclic loading conditions in [6], [7]. Wear resistance of this

material has been reported to be higher than other AA2124 matrix composites [8]. Another important feature of this material is the high specific modulus, defined as a ratio of Young's modulus to the mass density of the material, which is a key engineering attribute when designing for minimum structural weight is crucial. Materials with a high specific modulus are important in Aerospace, Automotive and Robotic systems. Figure 1 compares specific modulus of 2124/SiC/25p with that of other common alloys.

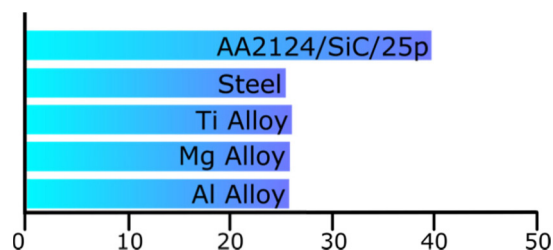


Figure 1. Specific modulus of 2124/SiC/25p Vs other common alloys [9].

2124/SiC/25p is produced using the powder metallurgy (PM) technology involving multiple operations; this makes this material expensive. However, this process is considered to be green as PM process releases very little fumes and chemicals to the atmosphere [10]. Further, there are two factors which can increase the potential of implementing this technology in high volume automotive manufacturing. The first is the opportunity to produce the composite through a lower cost route. And the second is a higher

production rate at a reduced cost and minimum material waste. The latter may be achieved by using a precision hot forging technology to manufacture components. Precision forging is described as a near-net-shape forging operation that produces high-quality parts regarding the surface quality and dimensional accuracy. A shorter production cycle due to minimal post-forge machining and a reduced material waste contribute to the cost reduction while meeting regulatory requirements and competitive pressures. The forging technology is particularly suitable for the production of high duty components such as pistons. Components forged from the Al/SiC composite shows higher tensile strengths and ductility than the cast components [11]. Further, this composite has been reported to have excellent forgeability [12] that allows forging of parts with complex geometry free of cracks in one forging operation.

This paper addresses some aspects of the precision hot forging of an automotive piston from 2124/SiC/25p composite manufactured using the lower cost route developed by Materion AMC.

In hot forging, the cost of tools accounts for a substantial fraction of the overall production cost. This is of particular significance in the closed die forging where the stresses in the tools can reach a high level at the final forming stage which may lead to the premature die wear /damage. This aspect has also been investigated and is presented in this paper.

PARTICLE REINFORCED AL ALLOY 2124/SiC

Particulate reinforced aluminium alloys are discontinuous reinforced metal-matrix composites, in which the addition of ceramic particles, to aluminium alloys through PM techniques creates a new class of materials with advantageous properties. Unlike continuous metal-matrix composites, these materials with discrete reinforcing particles within the parent alloy matrix, have been found to be workable by all existing metalworking techniques, including hot forging. Such feature makes these composites very attractive for a wide range of industrial applications. One of the discontinuous metal-matrix composite alloy based on 2xxx series which has become commercially available is 2124/SiC/25p [13]. The presence of reinforcement within the matrix; typically 10 to 40% in volume, leads to a significant modification of the characteristics of the parent alloy such as an increase in elastic modulus, strength and abrasion resistance, and improved properties at elevated temperatures. On the downside, reduction in ductility and fracture toughness is a design obstacle [14], [15].

The addition of particulate reinforcing to ductile alloy matrix also modifies the deformation behaviour and changes the flow stress [13], [16], [17]. At forging temperatures above 425 °C, for instance, flow stress is lower than monotonic 2124. The fabrication history of this material can also significantly impact the deformation in hot forging and development of the final mechanical property [18]. In other words, the process route is specified depending on the required mechanical property, component shape and cost constraints. The billet temperature for forging such materials has to be specified case by case, however typically temperatures higher than those used for their matrix alloys are necessary.

Forging programs have shown that MMCs based on the 2xxx series aluminium alloys can be successfully forged using high-definition closed-die forgings. The forged composite shows good mechanical strength and ductility [19]. Good hot formability of such composites is due to the small size of SiC reinforcement particles [12]. Some evidence suggests that these composites are more aggressive on closed-die tooling and that the die life in forging these materials may be shorter than that of a die used to forge their parent alloys [20]–[22].

2124/SiC/25p is manufactured through a special PM route to minimise a chemical reaction between metal matrix and ceramic particulates, ensuring the purity of the matrix alloy, along with using a patented high-energy mixing Mechanical Alloying (MA) process for excellent particle distribution. MA technique continuously mashes the components and breaks apart the mixture of AA2124 powder and ceramic reinforcement under a controlled condition, to produce an intimate and uniform mixture. This process can create high volume fraction of reinforcements with ultrafine particles. Fully dense billet is obtained by hot isostatic pressing (HIP) of the mixture. Billets are then used for direct manufacture to component or fabrication by hot forming processes such as forging and extrusion [23].

Some of the particle-reinforced composites are commercially available in the form of bars. MMC producers use hot extrusion of compacted billets to fabricate the composite bars. The conventional extrusion techniques are used to produce bar which improves the distribution and adhesion of reinforcement particles [9], [24].

Selection of the process route is closely associated with the required properties and the resulting process cost. High strength and high modulus of aluminium MMC are closely linked to particulate size and ceramic loading. Finer particle size effectively contributes to cost reduction in subsequent manufacturing stages such as extrusion and machining. On the flip side, a higher volume percentage of ceramic can adversely impact the wear of the machine tool insert.

The material used in this research was supplied by Materion AMC in Farnborough. Materion AMC has developed a lower cost processing route for manufacturing metal composites via a powder metallurgy route which produces a homogeneous distribution of SiC within the aluminium matrix. This is achieved with automation of the mechanical alloying process along with significantly increased yield from billet material. HIP process is used to produce the billets which are directly used for hot forging. [Figure 2](#) shows the block diagram of the process.

Mechanical testing has proved the mechanical performance of the lower cost route material. Rotating bend fatigue testing was carried out on 2124/SiC/25p produced using the standard route and the lower cost route. Results of this test shown in [Figure 3](#) indicate that at 315 °C (near the operating temperatures on the piston head) there is negligible difference between the standard route and the lower cost route when the fatigue strength is concerned. Also plotted in [Figure 3](#) is the known data for currently manufactured cast Al pistons. This indicates a fatigue strength at 1×10^7 cycles of 50 MPa, in the case of the 2124/SiC/25p, the fatigue strength at 1×10^7 is 100 MPa. This

clearly shows the improvement in mechanical performance between the MMC and the standard cast Al piston and the potential advantages of using the MMC to manufacture lighter pistons.

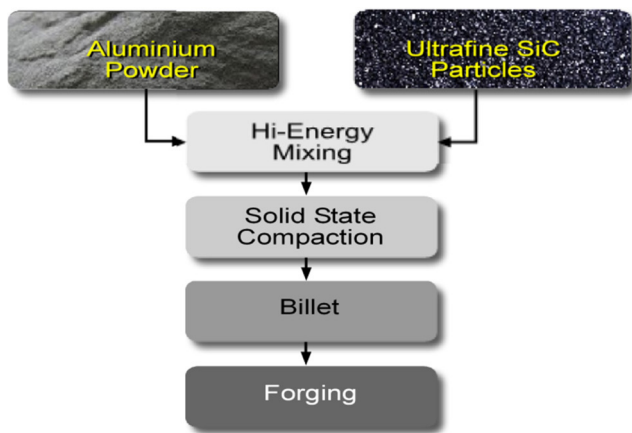


Figure 2. Block diagram of the material process route

The properties of 2124/SiC/25p and the parent AA2124 alloy are presented in Table 1.

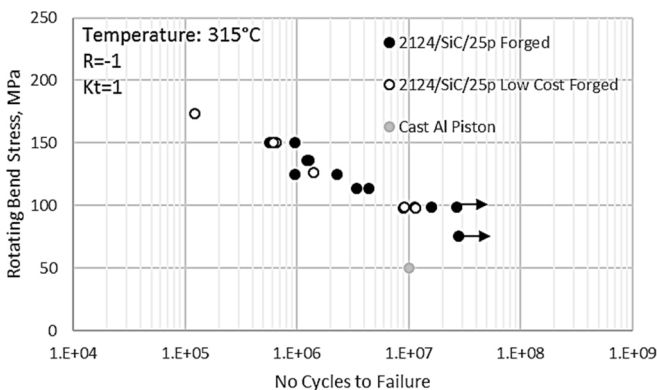


Figure 3. Rotating fatigue test results shows the 2124/SiC/25p from lower cost route has a very good fatigue strength

Table 1. Properties of 2124/SiC/25p [25] and AA2124 [26].

Property	2124/SiC/25p	AA2124
Young's Modulus	115 GPa	73.1 GPa
Ultimate Tensile Strength	680 MPa	483 MPa
0.2% Yield Strength	480 MPa	441 MPa
Poisson's Ratio	0.3	0.33
Elongation to Failure	5%	8%
Thermal Conductivity	150 W/m ^o C	151 W/m ^o C
Thermal Expansion Coefficient	15.5 ppm/ ^o C	22.9 ppm/ ^o C
Heat Capacity	0.836 J/g/ ^o C	0.882 J/g/ ^o C
Solidus	548 ^o C	502 ^o C
Liquidus	660 ^o C	638 ^o C
Density	2.88 g/cm ³	2.78 g/cm ³
Vickers Hardness	210	146
Average particle size	3 μ m	n/a

FORGING PROCESSES

In forging processes transfer of heat between the die and the workpiece results in thermal gradients in the workpiece, which causes a non-uniform plastic flow. This is called die chilling. Using the glass lubricant coating for the billets can create a thermal shield that partially helps to diminish this effect. In practice, forging dies are heated to reduce the chilling effect. Using fast-acting forging machines that have a short die-billet contact time, such as screw presses is another way of reducing this effect.

Heating the dies to the same temperature as the workpiece can completely remove the chilling effect, this is called isothermal forging. Aluminium alloys are usually forged using hydraulic presses under isothermal or near isothermal conditions at temperatures that do not significantly compromise the strength or hardness of the die material. The primary advantages of isothermal forging are achieving closer part tolerances, saving material and cost of subsequent machining. There may also be a reduction in tooling cost due to the slow process which needs lower forging pressures. However, more expensive die material and controllable die heating systems are required.

Alternatively, fast-acting screw presses deliver a high speed forging blow to reduce the contact time. Screw presses provide flexibility and control over a wide energy range, and their higher forging pressures make them suitable for the precision forging of a wide variety of parts. Screw presses have high repeatable accuracy and short cycle times that enhance productivity.

In this research both, hydraulic press isothermal forging and screw press hot forging of the piston were modelled using finite element method. The influence of forging parameters such as ram speed and billet temperature was studied to understand process response and material flow.

The geometry of the piston and its forged form (forging) are shown in Figure 4a and 4b, respectively. In order to create geometry suitable for forging some of the features such as boss pin holes and ring grooves have been removed and extra material added for post-forging machining. The forged form was used to design the punch and die geometry. The goal was to achieve near net shape forging including the crown feature on the piston head that could save material and machining cost. To achieve that, the modelling was first completed with flat piston head to grasp an overview of the process, and later simulation of forging the piston with the crown details was carried out. Parameters describing forging condition on both presses are shown in Table 2.