

# Forging of a MMC for an automotive component

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## Abstract

*A brake drum for automotive applications produced by MMC forging has been investigated. This component was chosen due to the high estimated weight reduction and to the relatively low mechanical properties required. Tribological and FEM thermal analysis have indicated 359/SiC/20p as the most attractive composite in replacing cast iron. The damage level in the forging has been calculated by means of an image analysis system. A higher damage level in the flash and corner regions has been found due to their stress and strain state. An improvement of the forging design and forging conditions is required for the production at low cost of defect free brake drums.*

## Riassunto

È stato effettuato uno studio di fattibilità per la fabbricazione di un tamburo freno per applicazione automobilistica mediante forgiatura di un materiale composito a matrice metallica (MMC). Le sollecitazioni meccaniche, non eccessivamente elevate, a cui è soggetto questo componente permettono l'impegno di un MMC in sostituzione alla ghisa, materiale tradizionalmente impiegato, garantendo un elevato risparmio in peso. L'analisi tribologica sperimentale e l'analisi FEM termomeccanica hanno indicato la lega 359/SiC/20p come materiale composito a matrice metallica più indicato nella sostituzione della ghisa. Il livello di danneggiamento del forgiato è stato calcolato mediante un analizzatore di immagine. È stato identificato un più alto livello di danneggiamento nella bava e nelle zone d'angolo per effetto delle tensioni più elevate e della più alta velocità di deformazione. Al fine di produrre un tamburo freno in MMC a basso costo mediante forgiatura, è necessario avvicinarsi il più vicino alla forma finale in modo da minimizzare le lavorazioni meccaniche successive. Per tale motivo è necessario un miglioramento sia nella progettazione dello stampo che nella messa a punto dei parametri di forgiatura.

## INTRODUCTION

The need of high performance and light weight materials has moved from the aerospace to the automotive industry. This industrial branch involves environmental and social problems, such as energy saving and recyclability, due to the large extent of its market. This situation has been received by the EEC which has recently proposed a legislation aimed to discourage fuel consumption and to favour recyclable can commercialisation. Moreover, factors associated with weight are the main reasons for car fuel consumption. These issues have led the automotive industry to find new low weight and recyclable materials. To this end, the attention has been focused on Metal Matrix Composites (MMCs); they can replace conventional materials in many structural applications since they offer high specific stiffness and strength, good thermomechanical behaviour and wear resistance (1,2). In particular, the extremely high sensitivity of car industry to production rate and material costs have driven experimental efforts on MMCs based on aluminium alloys reinforced with particles of ceramic materials such as Al<sub>2</sub>O<sub>3</sub> and SiC (3-6): they are more readily available at reasonable prices and can be processed using the technologies developed for monolithic alloys (7). A definitive kick off for this class of material depends on the development of processing techniques, close to

traditional high rate manufacturing processes for mass production, to enable the production of parts with complex geometry at reasonable cost. However, the high ductility and fracture toughness values required to satisfy car safety rules are very difficult to achieve in metal matrix composites (8). A BRITE-EURAM project, with funding from the EEC, which includes, besides the authors, a MMCs manufacturer two forging companies, two Universities and a Research Centre, is aimed at selecting both materials and candidate car components and to develop an effective forging route on an industrial scale, using particulate reinforced aluminium alloys matrix composites. The partners are pursuing this purpose taking into account many factors such as design, manufacturing economics, comparison between the performance of a MMC component and conventional material one, etc. In particular, hot deformation experiments have been performed for the determination of the best hot working conditions of the MMCs under investigation. This data was used as input to a finite element code to simulate the forging operation of the car component both on a macroscale and microscale. The numerical modelling permits the definition of the optimum manufacturing conditions (die and workpiece temperatures, die speed, lubrication and design) in order to obtain defect-

free components with the highest mechanical properties at the lowest cost (9).

In the present paper, a study dealing with the selection of: I) an automotive component to be produced by forging, and II)

the particle-reinforced aluminium alloy matrix composites meeting the component function, was performed. The forged part was systematically investigated by means of an image analysis system in order to evaluate the damage level of the forging.

## SELECTION OF A CAR COMPONENT

In the BRITE-EURAM project several car components have been considered such as the upper transversal arm of a multilink suspension and a brake drum. The first is a structural component and requires fracture elongation and toughness values which are unlikely to be achieved in forged MMCs although they may be improved by a proper definition of the forging conditions. On the other hand, since the brake drum

is not a structural component, the forging conditions and the MMC can be selected without the heavy requirements of the previous component. Furthermore, the estimated weight reduction (about 40%), arising from the substitution of grey cast iron with aluminium alloy matrix composites is beneficial. For this reason, in the first stage of the project the brake drum component has been studied.

## MATERIAL CHOICE

Among the Duralcan (USA) commercially available MMCs, aluminium alloy matrix composites with the highest volume fraction of reinforcement (20%) were chosen since their very good wear behaviour at high temperature meets the required targets of the brake drum component. Three MMCs were identified: 6061/Al<sub>2</sub>O<sub>3</sub>/20p, 359/SiC/20p and 2618/Al<sub>2</sub>O<sub>3</sub>/20p. The most effective material for the brake drum component, among the three different MMCs, has been established by means of a tribological analysis based on the pin on disk test. The tests were carried out using, as antagonist material, an

optimized friction material supplied by Allied Signal Automotive. The test parameters, representative of severe operation conditions, were: i) compressive stress: 5 Mpa; ii) sliding rate: 3.7 m/s; iii) test time: 300 s.

The results are shown in Figs. 1 and 2 where they are compared with cast iron. It can be observed that the temperature of the brake disk, measured by three thermocouples, increases with time and it is higher with cast iron than with 359/SiC/20p (Fig.1). The frictional coefficient values in 6061/Al<sub>2</sub>O<sub>3</sub>/20p and 359/SiC/20p are higher and more uniform than 2618/

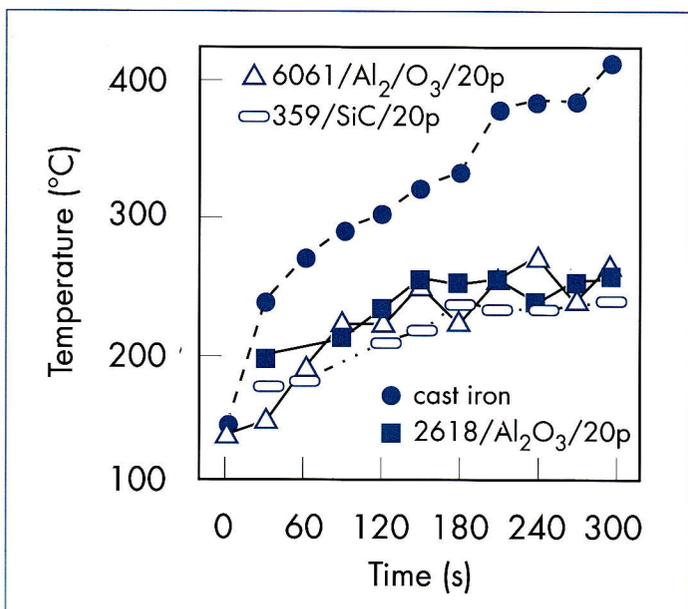


Figure 1: Temperature versus time for cast iron and the three MMCs investigated

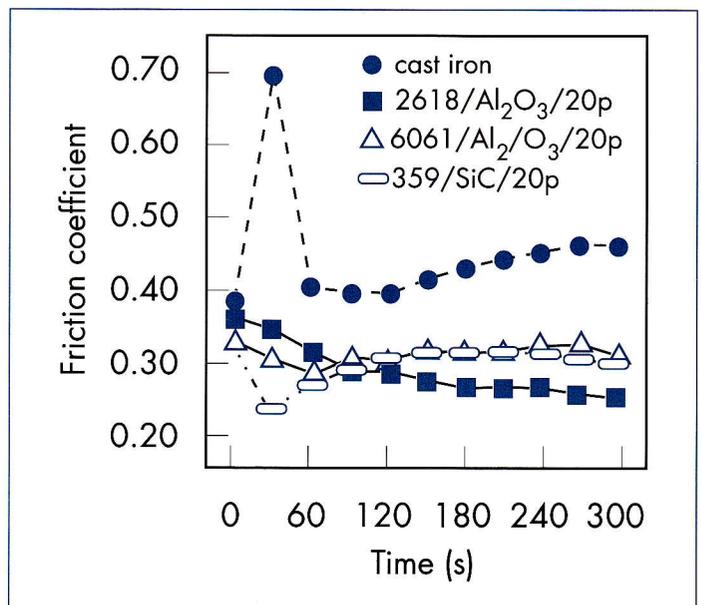


Figure 2: Frictional coefficient versus time for cast iron and the three MMCs investigated

Al<sub>2</sub>O<sub>3</sub>/20p although lower than the cast iron one (Fig. 2). These results indicate that, among the MMCs considered,

359/SiC/20p is the most attractive material in replacing cast iron in a brake drum component.

## THERMAL ANALYSIS OF THE BRAKE DRUM BY THE FINITE ELEMENT METHOD

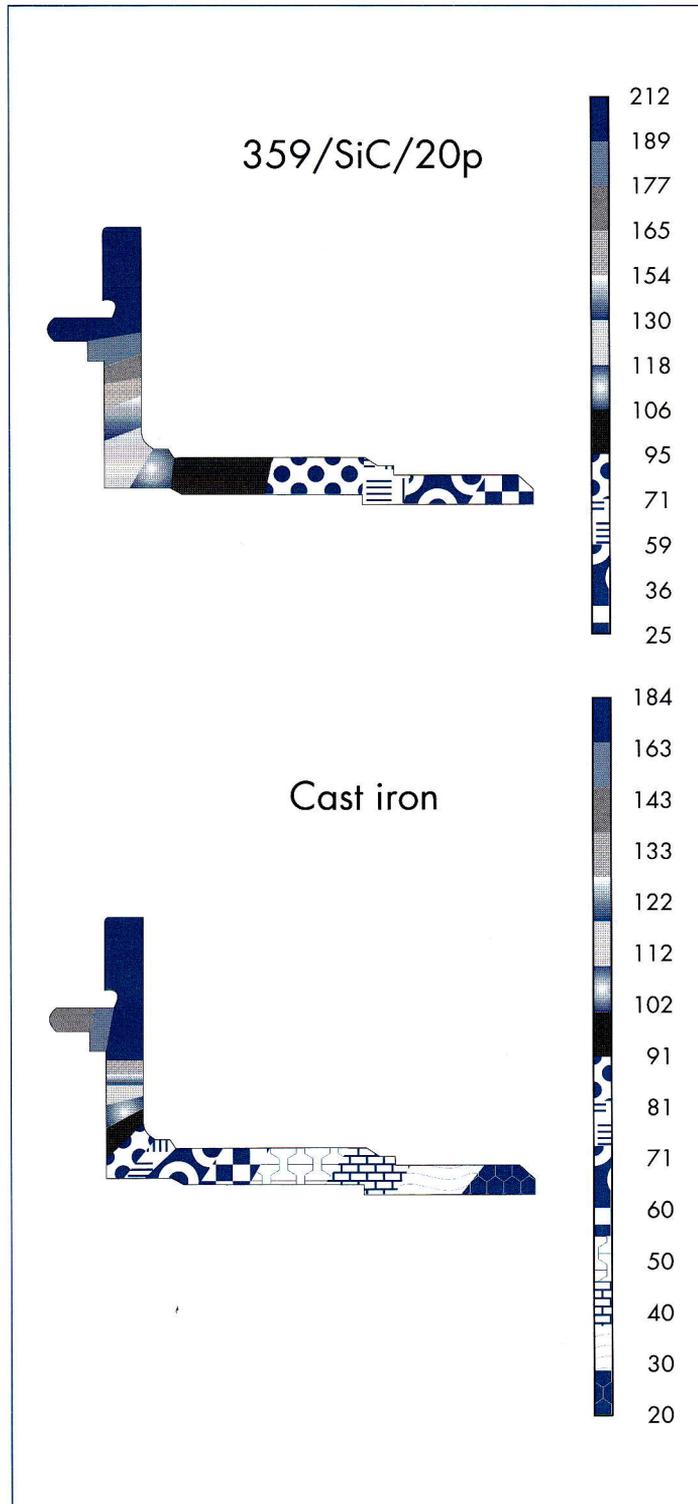


Figure 3: Temperature (°C) distributions predicted by the FEM across the brake drum section after 10 s braking with:  
 a) 359/SiC/20p  
 b) cast iron

A thermal analysis of the brake drum by means of the finite element method (FEM) was performed in order to evaluate the temperature distribution in the component during braking from 160 Km/h to 0 Km/h in 10 s. The thermo-physical properties of 359/SiC/20p composite were given by the material manufacturer. The boundary conditions set in the FEM model developed by the Fiat Research Centre take into account the thermal power: 1) dissipated by conduction to wheel hub, 2) by convection, and 3) generated by friction on rubbing surface. Fig. 3 shows the temperature distributions in 359/SiC/20p and cast iron after 10 s, respectively. Fig. 4 shows the comparison between maximum temperature versus time curves for the two different materials. The temperature distribution of 359/SiC/20p is more uniform, due to the higher thermal conductivity; moreover, the maximum temperature reached in the middle of rubbing surface with 359/SiC/20p (240°C) is lower than the cast iron one (270°C). The thermal analysis indicates that a good behaviour of the MMC brake drum component is predictable. However, other thermal calculations, taking into account different braking missions (i.e. repeated brakings) coupled with experimental analysis, are necessary before delivering the component. In particular, it will be important to verify that:

- the maximum temperature reached on rubbing surface is lower than the 359/SiC/20p limit before severe wear (400°C);
- the maximum temperature close to the wheel hub is suitable for traditional wheel bearing application (approximately 120°C continually and 180°C maximum).

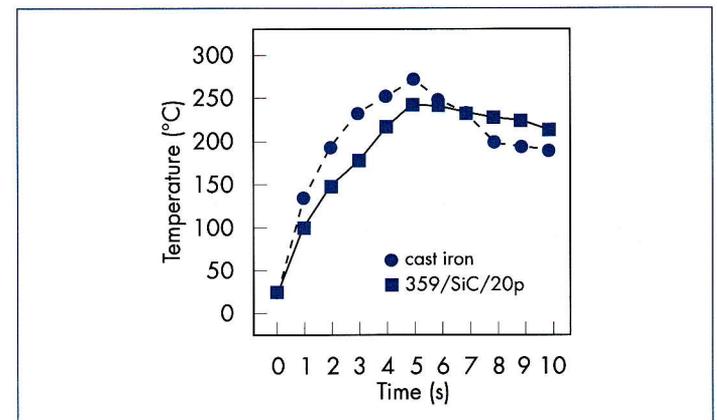


Figure 4: Maximum temperature versus time curves for 359/SiC/20p and cast iron during braking

## MATERIAL FORGING TRIALS AND EXPERIMENTAL TECHNIQUES

The MMC used in this investigation, 359/SiC/20p, was produced by mixing SiC particles, into molten A 359 aluminium alloy. The as-cast ingots were supplied in form of bars, with a diameter of 280 mm; no heat treatment was performed before forging. The nominal chemical composition of the A 359 alloy is the following: 8.5 - 9.5 Si, 0.2 Fe, 0.2 Cu, 0.50 - 0.70 Mg, 0.10 Zn, 0.20 Ti, Al balance.

The forging trials were performed at Stampal SpA, Italy, by means of a hydraulic press with a maximum capacity of 5000 tons at 300 bars. The initial billets, with a diameter of 260 mm and a height of 72 mm, were heated at 450°C for 1.5 h in a resistance furnace with forced ventilation; the dies were preheated in a furnace at 500°C and, after die set up, held by gas burners at about 360°C for the upper die and 320°C for the lower die. These temperatures were measured by means of two thermocouples inserted into the dies. The speed of the mobile die was pressure dependent. The lubricant used in the forging trials was a water-graphite solution (10:1 ratio) sprayed on a layer of animal fat with lead oxide

The forged component was designed for the production at the same 1/5 time of both brake drum and brake disk, by cutting the forging along the plane whose trace is the dashed line H-G of Fig. 5. In the present paper, only the brake drum has been considered.

A microstructural analysis, by means of optical microscopy, has been performed on both the as-cast and forged materials. This study aims to examine the changes in the distribution of the reinforcing SiC particles and Si precipitates occurring during the forging operation. To this end, the initial microstructure of the as-cast material was compared with the forging one. In the as-cast material, specimens were taken at the centre of the bar. In the forging, a 15 mm slice was cut from a longitudinal section lying on an axial plane; due to the symmetry of the forging, only one half of the section was examined.

## ANALYSIS OF THE FORGED COMPONENT

A microstructural analysis of the as-cast material is required before characterising the most relevant features of the forging. Fig. 6a shows the typical distribution of SiC particles in the as-cast material; it appears that such distribution is not homogeneous with the appearance of particle free zones and particle clusters with volume fraction of SiC particles higher than 20%. The SiC particles have a wide size distribution covering a range of about 5-18  $\mu\text{m}$  with a mean diameter of 9  $\mu\text{m}$ . The degree of damage in the as-cast material, measured by the ratio (Pv%) between the number of particles associated with voids and the total number of particles detected,

A further basilar aspect of the microstructural investigation was concerned with the level of damage introduced into the brake drum component by the forging process. Thus, the amount of damage present (holes, particle crackings, ...) was quantified versus the position in the forging in order to take into account the influence of the stress and strain states on promoting damage nucleation or growth. In particular, the number of particles associated with voids was measured in the most significative zones of the forging. The technique developed for the calculation of the damage used a Leica Quantimet 500 Image Analysis System. The different grey levels appearing in a video were used to detect the SiC particles, Si precipitates and cracked areas. The statistical accuracy of the measurement was ensured by examining about 500 particles for each area detected.

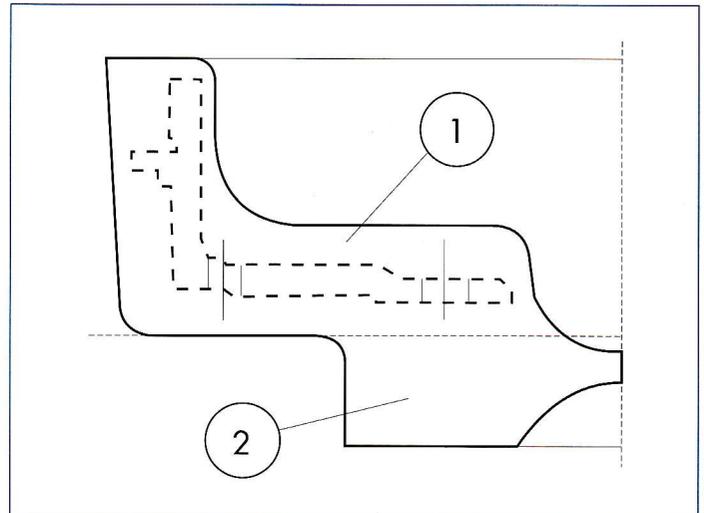


Figure 5: Forged component drawing with the superimposition of the brake drum

was obtained by means of the image analysis system previously described. The damage level calculated was about 3%; most of the defects were small holes at the matrix-particle interfaces although the presence of very few but strongly localized zones of damage associated with SiC clusters was seen (Fig. 6b). This may be attributed to gas entrapment during the casting process.

The forged part, obtained with a single step operation, showed no macroscale defects. The microstructural analysis revealed that the forging process reduces the material inhomogeneities (10). Fig. 7c shows that the SiC particles and the Si pre-

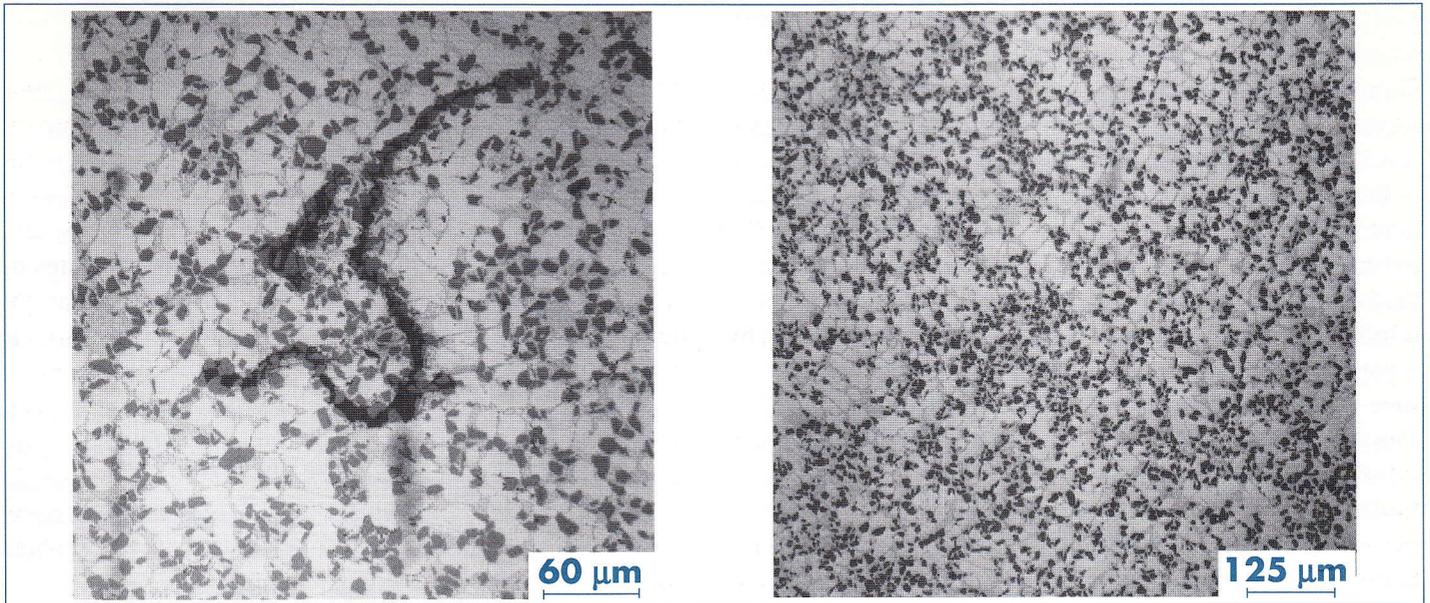
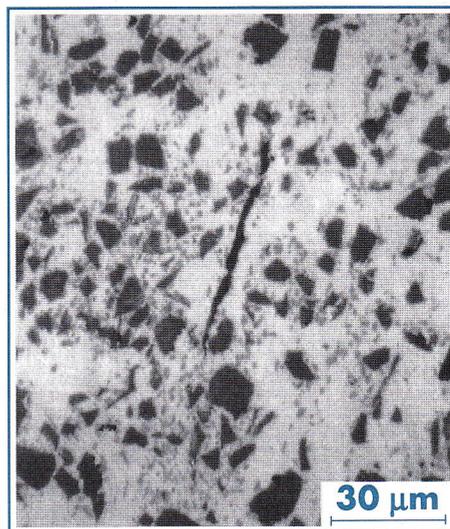
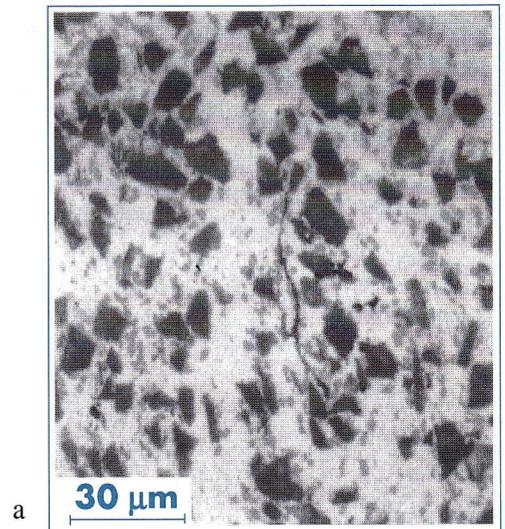


Figure 6: Optical micrographs of 359/iC/20p, prior to forging, showing: a) SiC particle distribution; b) cracks at SiC clusters

cipitates arrange according to the material flow; there is less evidence of particle clusters. Moreover, the aspect ratio and the range size of the SiC particles is not significantly changed. A low amount of damage present as holes and particle crackings is the first requirement for a well made forging component because they affect mechanical properties and fatigue strength. Therefore, the knowledge of the damage level in the different zones of the forging is extremely important in order to evaluate the effectiveness of the component. Fig. 7e shows the damage level measured as Pv% in the most representative zones of the forging; some critical areas, such as the corners B, C, D, E, F and the flash region A (Fig. 7a), have a higher, level of damage. The high level of damage observed in the flash region can be attributed to the high strain rate in such zone which may exceed the critical value predicted by Humpreys and Kalu (11) resulting in a build up of stress at the matrix-particle interfaces. Furthermore, the tensile stress state in the flash strongly reduces the ductility of the material. In the other critical areas, such as C and E, the high values of strain predicted by Roberts et al (12) should be responsible for the high level of damage. Figure 7e also shows a decrease in Pv% from the external to the internal regions of the forging. This can be attributed to the cooling of the external regions which are closer to the die. It causes an increase in flow stress and a reduction of the rate of stress relaxation mechanisms (13). As a consequence, stresses build up at the matrix-particle interfaces and are relaxed by particle cracking and/or interface debonding (14). The hydrostatic stress state, in the internal regions such as G, H and I, leading to a void closure, produces values of Pv% lower than or equal to the as-cast material one. However, a finite element



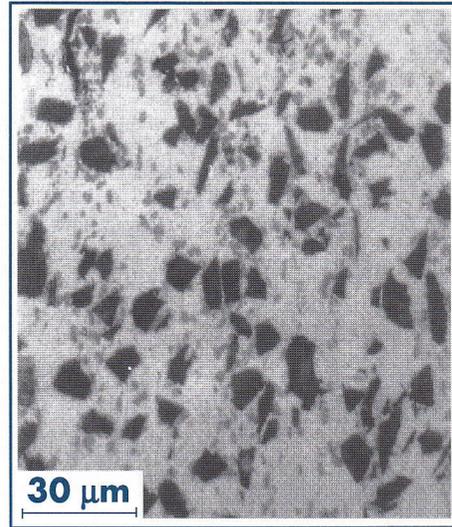
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analysis of the forging process is required in order to have a more exhaustive knowledge of the defect formation.

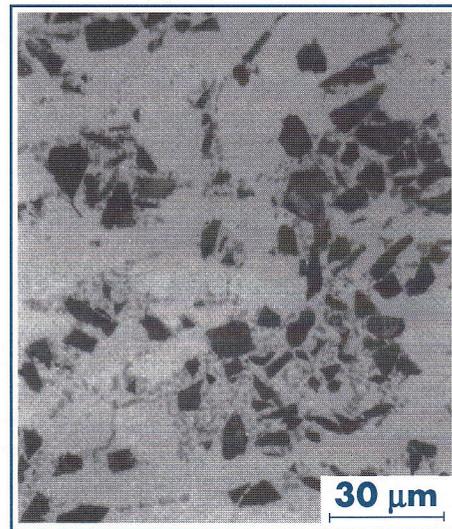
Figures 7b, c and d also show that damage in the E, B, and C regions is mainly due to particle fracture and particle-matrix decohesion. Furthermore, there is evidence of extensive cracks in the matrix associated with agglomerations of Si precipitates which were coalesced during forging operation.

In Fig. 7e the final brake drum (dashed line) is overlapped to the forging. It can be seen that the most damaged areas of the forging are located out of the finished part; only the F region is partially included into the brake drum. However, the stress state in such zone during braking is negligible.

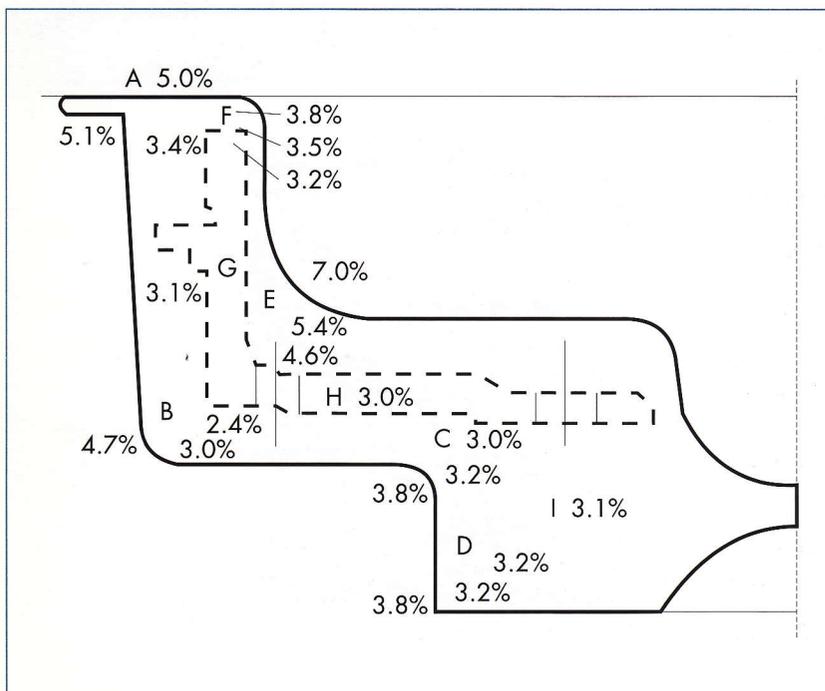
The very low overall damage level in the finished brake drum satisfies the soundness requirement of the component. The finished part has been obtained by machining the most critical regions of the forging. This causes a remarkable increase in manufacturing costs due to the very low machinability of the MMCs. A more accurate design of the forging, involving a reduction of the swarf, will increase the extension of the areas with high level of damage in the finished part. This approach reduces the production costs but could lead to unsatisfactory mechanical properties. In this case, the obtaining of a sound brake drum depends on the proper definition of the forging conditions such as workpiece and die temperatures, die speed and lubrication (15).



c



d



e

Figure 7: Optical micrographs of the forging microstructure in a) A region; b) E region; c) B region; d) C region; e) map of level

## CONCLUSIONS

In the present paper, the possibility of auto weight reduction by replacing conventional material components with low cost MMC components has been examined. A brake drum was selected as it does not require the high toughness and fracture elongation values of other structural components which are difficult to obtain in MMC forgings. Among the MMC candidates to replace cast iron, 359/SiC/20p appears most favorable in reducing temperature during braking. The forging trials were performed in working conditions similar to the unreinforced aluminium alloy ones; the forged part have shown no macroscale defects. An analysis of the forging have shown that the damage levels in the flash region and in most of the component corners are higher than in the as-cast material. This should be attributed to the stress and strain states in such regions. Most damaged zones are located out of the finished brake drum and as a consequence are removed by machining. A more accurate forging design and a proper definition of the forging conditions are required for a low cost manufacturing of defect-free MMC brake drum component.

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