Thermal expansion and fatigue properties of automotive brake rotor made of AlSi–SiC composites

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Abstract
Al-9Si–SiC or Al-12Si-SiC composites reinforced with 10 or 20 wt% SiC particles were synthesized by stir casting method. The composites were used to produce automotive brake rotors. Microstructures of the brake rotors made of the composites revealed uniformly distributed SiC particles, primary phase (α-Al) and modified eutectic Si. Grain refining was also observed due to the addition of SiC particles. Coefficient of thermal expansion (CTE) and thermal strain responses during heating and cooling cycles between room temperature and 350 °C of the composites were investigated. Al-12Si and its composites exhibited lower CTE and near zero residual strain. Thermal fatigue studies were carried out on the brake rotors made of the composites as well as commercially available brake rotor made of cast iron, for comparison. After 80 cycles, hardness measurements, microstructure investigations and x-ray diffraction (XRD) analysis were carried out. The results showed that the strain and temperature followed the same path on cooling as on heating, indicating that both hysteresis loop and residual strain were absent. At the same time, the crystallinity of the brake rotor made of the composite was enhanced by the exposure to thermal cycling, while it was deteriorated in case of break rotor made of cast iron on the long run.

1. Introduction
Because of oil crisis and environmental problems, reduction of fuel consumption and its emissions becomes a subject of great importance. Metal matrix composites (MMCs) offer outstanding properties such as light weight, high mechanical and tribological properties. Thus, they are recommended to replace steel and cast iron parts in automotive industry. As composite materials are tailor-made materials, the selection of the type of matrix, reinforcements and fabrication method depend mainly on the desirable properties according to the required applications [1]. Usually, MMCs are manufactured by dispersing reinforcements, which are added to metallic matrix to enhance the mechanical and tribological properties. Aluminium and its alloys are the most commonly used metallic matrices based composites. The addition of reinforcement such as SiC particles into aluminium and its alloys enhances the tensile strength, hardness and wear resistance [2]. Therefore, aluminium based composite could be a strong candidate in various applications, including automotive, aerospace, and electronic applications [3]. Aluminium and its alloy based composites can be manufactured by different techniques [4–8]. Dispersion process such as stir casting, where the particles are added and dispersed into the liquid aluminium alloy by using mechanical stirring, is the most economic technique [6, 7]. The distribution of the particles in the matrix alloy plays a significant role in determining the properties of the composites. Uniform particles distribution in the Al matrix can be achieved by selecting suitable processing parameters such as melt temperature, addition rate of the particles as well as stirring speed and time.

Automotive brake rotors are exposed to large thermal stresses during routine barking and extreme thermal stresses during hard braking, where the kinetic energy converts to thermal energy by friction during braking [9]. About 70% of the total kinetic energy dissipates via the front disc brakes [10]. It is well known that thermal strain can be attributed to thermal stress, which means that higher thermal stress can lead to generation of strain hysteresis between heating and cooling cycles. Also, thermal stress can cause retention of residual strain of plastic...
deformation or yielding of the materials. Data extracted from thermal response curves can provide the required information to predict thermal stability, failure/damage and life of the components that have been subjected to heating and cooling conditions [11]. About 80% of failures of automotive components are due to various types of fatigue. It has been found that the main reason of thermal cracking of automotive disc brakes is the low cycle thermo-mechanical fatigue, which occurs on the brake disc’s friction surface [12]. Thermal fatigue is the main type of failure of components that are exposed to hot working [13]. Thermal fatigue is produced basically by cyclic or periodic temperature changes and complete or partial restriction of thermal deformation due to external or internal constraints. These constraints produce forces that act on a component heated and cooled alternately, leading to fatigue cracking at the location with stress concentration caused by the restriction of thermal deformation [14].

Several studies were carried out to produce and investigate the properties of brake rotors made of Al based composites. Some of the studies used finite element programs to expect properties [15–17]. Some researchers tried to produce brake rotors made of aluminium based composites by using sand casting [18] or die casting [17].

As far as we know, there is no previous work dealing with fabricating automotive brake rotors from AlSi alloys reinforcing with SiC particles using stir casting technique, which is the most economic method to produce composites, and casting in a permanent mould.

The aim of the present work is to investigate the microstructure characterizations, thermal expansion and thermal fatigue properties of the manufactured automotive brake rotors made of Al-9Si or Al-12Si alloys reinforced with 10 or 20% SiC particulates using stir casting method.

### 2. Materials and experimental techniques

Brake rotors made of Al-9%Si or Al-12%Si reinforced with 10 or 20 wt% SiC particles having a size of 36 μm were fabricated by stir casting method and casting in a permeant mould. The chemical compositions of the matrix alloys are given in Table 1. Samples for microstructure investigations, thermal expansion and thermal fatigue testes were cut from the hub of the brake rotor.

Heat treatment was carried out on all samples according to ASTM B917-01 standard of Al alloys heat treatment. It was applied through two stages; the first stage was solution treatment by heating samples up to 540 °C for 10 h then water quenching at 80 °C and the second stage was aging, which was carried out by heating the samples up to 155 °C for 8 h then water quenching. Specimens for metallographic investigations were prepared using standard procedures and etched with ½ HF solution. Metallographic examinations were carried out by using Field Emission Electron Microscope (FEM), model FEI quanta FEG250, Netherland.

Specimens with the dimensions of $20 \times 5 \times 5$ mm were used for measuring the coefficient of thermal expansion (CTE). The CTE measurements were performed from room temperature to 350 °C at a rate of 5 °C min$^{-1}$ under protective atmosphere of argon using a dilatometer L75/L76 equipped with standard expansion probe. Standard dilatometer L75/L76 data analysis software was used to calculate the CTE.

Thermal fatigue testes were carried out using a muffle furnace (Ney Vulcan 3–550) on samples cut from the manufactured brake rotors made of composites and commercially available brake rotor made of cast iron. The thermal cycle consisted of heating the samples in atmospheric air at 350 °C for 15 min and then quenching into ice water for 5 min. After 80 cycles, the specimens were ground and polished for metallographic examinations. The crack propagation was examined by OLYMPSUS B202 optical microscope.

X-ray diffraction (XRD) analyses were carried out on the manufactured brake rotors made of composites and brake rotor made of cast iron before and after thermal fatigue tests. The crystal plane spacing ($d$) in a given direction was determined from the peak position using Bragg’s law:

$$d = n \lambda / 2 \sin \theta$$

Where $n$ is the reflection order (usually, only the first order is encountered for most common crystal structures), $\lambda$ is the radiation wavelength, $d$ is the plane spacing and $\theta$ is the diffraction angle. The strain is then given by:

$$\varepsilon = (d - d_0) / d_0$$

Where $\varepsilon$ is the strain in a particular direction, $d$ and $d_0$ are stressed and unstressed inter-planar spacing, respectively.

| Alloy | Si    | Mg    | Cu    | Zn    | Fe    | Mn    | Al  |
|-------|-------|-------|-------|-------|-------|-------|-----|
| Al-9Si| 8.79  | 0.393 | 0.314 | 0.0124| 0.113 | 0.0333| Rest|
| Al-12Si| 12.36 | 1.190 | 1.480 | 0.0407| 0.694 | 0.0184| Rest|
The crystallite size was calculated using Scherrer’s formula:

\[ D = \frac{k\lambda}{\beta \cos \theta} \]

Where \( k \) is taken as 1 and \( \beta \) is the full width of half maxima (FWHM) of the peak. The grain size was calculated around the most intense peak.

The abbreviations of fabricated brake rotors (matrix alloys and composites) and the cast iron one are presented in Table 2.

### 3. Results and discussions

#### 3.1. Microstructures

Figures 1(a)–(d) shows the microstructures of fabricated brake rotors made of the composites. The main microstructural features of A91 and A92 composites are primary phase (\( \alpha \)-Al) and a partially modified eutectic Si (marked by white arrows) due to the heat treatment, figures 1(a), (b). The figures, also, reveal a uniform distribution of SiC particles (marked by red arrows), which can be attributed to the selection of suitable processing parameters such as melt temperature, addition rate of the particles, stirring speed and time as well as casting in metallic mould. However, the microstructures of A121 and A122, figures 1(c), (d), show a relatively...
uniform distribution of SiC particles (marked by red arrows). Also, it can be noted that the addition of SiC particles leads to a considerable refining effect in the primary phase (α-Al) of the matrix alloys. Because of the lower thermal conductivity of SiC particles, the dendrites nucleate and grow away from the SiC particles and due to the restriction offered by SiC particles, a finer grain structure is developed. Thus, grain refining is achieved, especially, around the SiC particles. Microstructures in figures 1(a)–(d) show the presence of eutectic phase around SiC particles. The SiC particles are mainly located between dendrite arms, which means that SiC particles are pushed by the primary dendrites and gathered at eutectic zones because the specific heat of SiC particles is higher than that of molten AlSi matrix alloys. As the SiC particles are rejected into the liquid by the growing primary α phases, the remaining eutectic melt is rich in SiC particles [19, 20]. In figures 1(a)–(d) some SiC particles are connected by eutectic Si phase for the reason that the eutectic Si nucleates on SiC particles in Al-Si alloy, in agreement with the investigation done by Wu et al [21].

3.2. Coefficient of thermal expansion (CTE)

Figure 2 shows the coefficients of thermal expansion of the fabricated brake rotors. It can be noted that the brake rotor fabricated from A9 matrix alloy exhibits the highest CTE. However, brake rotors made of Al-9Si-20wt% SiC composites have the lowest CTE. The CTE of brake rotors fabricated from Al9Si matrix alloy is decreased by increasing the weight percent of SiC particles. According to Turner’s [22], this may be due to some factors such as the percentage of SiC particles added because the SiC particles have low thermal expansion coefficient than that of the matrix alloy. Another factor is the mismatch in CTE between matrix alloy and SiC particles, which causes internal stresses near the interface, leading to elastic strain in the matrix alloy [23]. In contrast, CTE of brake rotors made of Al-12Si matrix is not significantly influenced by the addition of 10 or 20 wt% SiC particles, where the change in the CTE between matrix and 20% SiC is marginal. This can be attributed to the presence of high percentage of eutectic Si phase and some primary Si, which are coherent with matrix and have lower CTes than that of Al. In other words, the high percentage of Si in Al-12Si has the dominant influence in decreasing the CTE rather than the addition of SiC particles.

3.3. Thermal cycles

Figures 3(a)–(f) demonstrates the thermal expansion behaviour of the produced brake rotors during heating and cooling cycles between room temperature and 350 °C. Addition of 10 wt% SiC particles to Al9Si matrix alloy increases the magnitude of hysteresis loop, which means that the residual stresses and strain are increased as shown in figures 3(a), (b). In spite of decreasing the CTE by the addition of 20 wt% SiC into Al-9Si matrix alloy, residual strain is not decreased, figure 3(c). This can be attributed to the residual stresses that generate as a result of heating and cooling cycles. In other words, the thermal cycles generate tension in the matrix and compression at the SiC particles, which result in residual strain, especially, at the particle matrix interface [24].

Thermal strain response curve of A12 matrix alloy shown in figure (d) reveals a small hysteresis loop. Also, the addition of 10 wt% SiC particles to Al-12Si matrix alloy leads to smaller magnitude of hysteresis loop as shown in figure 3(e). Increasing the amount of SiC up to 20 wt% decreases the magnitude of hysteresis loop, which disappears in figure 3(f). Okumus et al [24] have reported that the CTE of particle reinforced metal matrix composites is influenced by the interfacial reactions between particles and matrix as well as the plasticity due to CTE mismatch between particles and matrix during heating and cooling. In case of Al-12Si matrix alloy, SiC particles are uniformly distributed in the matrix alloy, while eutectic phase and primary Si are nucleated on the SiC particles during solidification as shown in the microstructures, figures 1(c), (d). CTE mismatch between SiC...
particles and Si is insignificant as reported by Leisen et al [25]. As a result of that, hysteresis loop disappears, specially, in case of addition of 20wt% SiC particles as shown in figure 3(f).

3.4. Thermal fatigue

Figures 4(a)–(f) shows the microstructures of brake rotors made of composites and commercially available brake rotor made of cast iron after 80 cycles of thermal fatigue test. By investigating figures 4(a)–(f), it can be noted that there are no cracks as a result of thermal fatigue cycles. Also, no macroscopic cracks along the interface between matrix alloy and SiC particles are detected, signifying that a strong interfacial bond has been developed between the matrix and SiC particle and the internal thermal stresses, resulting from the mismatch between the SiC particles and the matrix, are insignificant. In other words, the resistance of matrix alloys to the thermal fatigue crack initiation and propagation is enhanced by the addition of SiC particles as well as the strong bond developed between the matrix and SiC particles [26, 27]. It has been reported that hardness of a specimen provides strong evidence regarding the amount of residual stresses that have been formed during thermal cycling [28]. Thus, hardness has been measured for the investigated specimens before and after thermal fatigue tests.

Table 3 presents the hardness values of the investigated materials. It can be observed that there is a huge decrease in hardness value of all the materials before and after thermal fatigue test. This indicates that the stress relief dominates over stress generation, resulting from relaxation of dislocations through moving of fixed dislocations anew and cancelling each other out. This leads to decreasing both dislocation density and, thus, hardness of the material [29]. The decrease in hardness of thermal cycled composites is due to metallurgical

![Figure 3. Thermal strain response curves during one cycle of heating and cooling between room temperature and 350 °C, (a) A9, (b) A91, (c) A92, (d) A12, (e) A121, (f) A122.](image-url)
transformations in the matrix alloy such as recovery rather than the physical damage of the composite (interface de-bonding) as reported by Hall and Patterson [30].

XRD combined curves (before and after thermal fatigue tests) of the produced brake rotors made of composites and cast iron are illustrated in figures 5(a)–(e). Tables 4 and 5 present the detected parameters ($\theta$, $d$ and FWHM) from XRD patterns and the difference in line breadth of the investigated specimens at the maximum intense peak in XRD curves, respectively. From table 4, it can be observed that no +ve strain is occurred, indicating that the strain and temperature follow the same path on cooling as on heating. Both the hysteresis loop and residual strain are

Figure 4. Microstructures of brake rotors made of composites after thermal fatigue test and brake rotor made of commercial cast iron before and after thermal fatigue test (a) A91, (b) A92, (c) A121, (d) A122, (e) CI before thermal fatigue and (f) CI after thermal fatigue.
absent in case of the composites [31]. The residual stresses relax during isothermal exposure and less internal stress is present to drive polygonization recovery. The two effects; thermally activated recovery in the matrix and relaxation of thermal stresses are competing mechanisms for reduction of strength [32, 33]. Also, it can be noted from table 4

Figure 5. XRD of the prepared brake rotor made of composites before and after thermal fatigue test, (a) A91, (b) A92, (c) A121, (d) A122, e (Cl). ΔBreath (ΔB) = B2 – B1.
that the FWHM for the maximum intense peak decreases after thermal cycling for all specimens. By applying Scherrer’s formula, the crystallite size \(D\) increases after thermal cycling for all specimens, especially, the composites. This can be attributed to the higher thermal conductivity of the composite, which enhances the heat transfer through the matrix rather than storing the heat. In addition, the slight difference between 

**Table 3.** Hardness of brake rotors made of composites and cast iron before and after thermal fatigue test.

| Specimen | A91 | A92 | A121 | A122 | CI |
|----------|-----|-----|------|------|----|
| Hardness(Hv)\(_{\text{before}}\) | 140 | 163 | 150 | 184 | 208 |
| Hardness(Hv)\(_{\text{after}}\) | 24 | 32 | 22 | 45 | 120 |

**Table 4.** Crystallite size (\(D\) (angstrom)) and XRD parameters (\(\varepsilon\), FWHM) of the produced brake rotors made of composites and cast iron before and after thermal fatigue test.

| Parameter | A91 | A92 | A121 | A122 | CI |
|-----------|-----|-----|------|------|----|
| \(D_1\) (before) | 2.34137 | 2.34245 | 2.34156 | 2.34206 | 2.03045 |
| \(D_2\) (after) | 2.33989 | 2.34156 | 2.34059 | 2.34164 | 2.03029 |
| \(\varepsilon\) | \(-0.72\times10^{-5}\) | \(-0.38\times10^{-5}\) | \(-0.41\times10^{-5}\) | \(-0.18\times10^{-5}\) | \(-7.88\times10^{-5}\) |
| FWHM 1 \(\omega\) (before) | 0.3346 | 0.3149 | 0.3149 | 0.2952 | 0.4133 |
| FWHM 2 \(\omega\) (after) | 0.3149 | 0.2558 | 0.2755 | 0.2755 | 0.2362 |
in $\varepsilon$ indicates that there is no distortion occurred in crystallinity of the specimen after thermal cycles, especially in case of the composites. From the above data, it can be concluded that the produced composites lose their heat continuously and the strain hysteresis loop is not formed between the heating and cooling cycles. In other words, the strain and temperature follow the same path on cooling as on heating, which means that both the hysteresis loop and residual strain are absent. Also, from figures 5(a)–(d), the difference in breadth of all diffraction peaks for the maximum intense peak was calculated and given in table 5. For A91 and A92 composites, the breadth decreases after exposure to thermal cycles by 0.38° and 0.418°, respectively, figures 5(a), (b). A121 composite exhibits decrease in the line breadth after exposure to thermal cycles by 0.19°, figure 5(c). Figure 5(d) shows the XRD combined pattern for A122 composite. It can be seen that there is no change in line breadth after thermal cycles, table 5. From these results, it can be concluded that the loss of micro-strains is in the crystallite. Figure 5(e) shows the combined XRD curves for brake rotor made of cast iron. Unlike the composites, the increase in line breadth after exposure to thermal cycles is 0.76°, table 5. This is due to the micro-strains that are formed as residual strains after exposure to thermal cycles. Actually, the broadening in the crystallite is primarily a result of two related phenomena: a reduction of the crystallite and an increase in the range of micro-strain [34]. When a material is strained by thermal cycles, the perfect crystalline regions between dislocation tangles become smaller. When these regions are reduced to less than 0.1μm, the diffraction peak breadth increases with further reduction. The micro-strains in each crystallite vary around the mean value for the aggregate of such regions, making up the polycrystalline body. This range of micro-strains results in variation in the lattice spacing of the diffracting crystallites and increasing line broadening [34].

From the above results, we can conclude that the crystallinity of the produced brake rotors made of composite improves by exposure to thermal cycles, while crystallinity of brake rotor made of cast iron deteriorates on the long run.

### 4. Conclusions

1. Brake rotors made of composites are successfully manufactured from Al-9Si and 12Si reinforced with 10 and 20% SiC by using sir casting method.
2. Microstructures of the produced brake rotors show primary phase ($\alpha$-Al) and an eutectic mixture of Al and Si that is modified to spheroidized shape as a result of heat treatment.
3. The addition of SiC particles and their uniform distribution in the matrix alloys lead to a significant refining effect in the matrix alloys.
4. The coefficient of thermal expansion decreases by increasing the Si content and the weight percent of SiC particles.
5. Increasing Si content and weight percent of SiC particles decrease the residual strain to be zero.
6. The produced brake rotor made of composites reveals higher thermal fatigue resistance than that of cast iron brake rotor.

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References

[1] Schulz B F and Rohatgi P 2012 Metal matrix composites offer the automotive industry an opportunity to reduce vehicle weight, improve performance Advanced Materials & Processes 19–23

[2] Ralph B, Yuen H C and Lee W B 1997 J. Mater. Proc. Technol. 63 339

[3] Chawla N and Chawla K K 2013 Meal-Matrix Composites 2nd edn (New York: Springer Science) 978-1-4614-9548-2 (ebook) [https://doi.org/10.1007/978-1-4614-9548-2]

[4] Macek O B 2005 Metal matrix composites—from science to technological significance Compos. Sci. Technol. 65 2526–40

[5] Adrian P P and Ghorbhe B M 2010 Manufacturing and process and applications of composite materials, ANNALS of the ORADEA UNIVERSITY Facsicle of Management and Technological Engineering IX NR2

[6] Reddy Nagavally R 2016 composite materials, history, types, fabrication techniques, advantages and application International Journal of Advances in Science Engineering and Technology vol 4 (Indiac: Institute of Research and Journals) 87–92 Iss-3, Spl. Issue-2

[7] Hashim J, Looney I and Hashim M S J 1999 Metal matrix composites: production by the stir casting method J. Mater. Process. Technol. 92–93 1–7

[8] Ramnath B V, Elancherian C, Annamalai R M, Aravind S, Atreya T S, Vignesh V and Subramanian C 2014 Aluminium metal matrix composites-a review Rev. Adv. Mater. Sci 38 35–60

[9] Peve M, Oder G, Potre I and Sraml M 2014 Elevated temperature low cycle fatigue of grey cast iron used for automotive brake discs Eng. Fail. Anal. 42 221–30

[10] Sethupathi B, Muthuvel A, Prakash N and Louis S W 2015 Numerical analysis of a rotor disc for optimization of the disc materials Journal of Mechanical Engineering and Automation 5 5–14

[11] Ren S, He X, Qu X, Huamai I and Li Y 2007 Effect of Mg and Si in the Aluminium on the thermos-mechanical properties of pressureless infiltrated SiCp/Al composites Compos. Sci. Technol. 67 2103–12

[12] Mackin T J, Noe S C, Ball K J, Bedell B C, Mered D P and Bingman M C 2002 Thermal cracking in disc brakes Eng. Fail. Anal. 9 63–76

[13] Zhang X, Du T and Zhang Y 2011 Prediction of thermal fatigue life of a turbine nozzle guide vane Journal of Zhejiang Univ-Sci A (Applied Physics & Eng) 12 214–22

[14] Korb G and Neubauer E 2001 Thermophysical properties of metal matrix composites MMC-Assess Consortium 73

[15] Adebiit, A A, Maleque M A and Shah Q H 2011 Surface temperature distribution in a composite brake rotor International Journal of Mechanical and Materials Engineering (IJMME) 6 356–61

[16] Govindan M and Viji B 2017 Design and analysis of automobile brake disc by using AI/SiC MMC International Journal of Innovative Research in Science, Engineering and Technology 6

[17] Sadagopan P, Harish Karthi N and Praveen Kumar J 2018 Study of silicon carbide-reinforced aluminium matrix composite brake rotor for motorcycle application Int. J. Adv. Manuf. Technol. 94 1461–75

[18] Daoud A and Abou El-Khair M T 2010 Wear and friction behaviour of sand cast brake rotor made of A359-20 vol% SiC particle composites sliding against automobile friction material Tribology International 43 544–53

[19] Aigbodion V S and Hassan S B 2007 Effect of silicon carbide reinforcement on microstructure and properties of cast Al-Si-Fe/SiC particulate composites Mater. Sci. Eng., A 447 355–60

[20] Xu J, Liu X, Barbero E, Hemrick J G and Peters M 2007 Wetting and reaction characteristics of Al2O3 /SiC composite refractories by molten aluminium and aluminium alloy Int. J. Appl. Ceram. Technol. 4 514–23

[21] Wu S, You Y, An P, Kanno T and Nakae H 2002 Effect of modification and ceramic particles on solidification behaviour of aluminium-matrix composites J. Mater. Sci. 37 1855–60

[22] Makarian K, Santhananam S and Wing Z N 2016 ‘Coefficient of thermal expansion of particulate composites with ceramic inclusions Ceramic international 15 17659–65

[23] Cao R, Jiang J X, Wu C and Jiang X S 2017 Effect of addition of Si on thermal and electrical properties of Al-Si-Al2O3 composites IOP Conf. Ser.: Mater. Sci. Eng. 213 012001

[24] Okumus C C, Aslan S and Karisluoglu B 2012 Thermal expansion and thermal conductivity behaviours of Al-Si/SiC/graphite hybrid Metal Matrix Composites (MMC) 18 341–6

[25] Leisem D, Jakovlev O, Kehltembach P, Riesche-Oppermann H, Eberl C, Fuchs T and Kraft O Measuring The coefficient of thermal expansion of silicon carbide thin films using digital image correlation, Karlsruhe Institute of Technology (KIT) [https://pdfs.semanticscholar.org/7885/c46e9f91bc266423c7b6e29bf9d71f4f9.pdf_ga=2.136893680.1937663788.1576777727-1344910590.1576777727 www.kit.edu]

[26] Zheng X, Du T and Zhang Y 2011 Prediction of thermal fatigue life of a turbine nozzle guide vane Journal of Zhejiang Univ-Sci A (Applied Physics & Eng) 12 214–22

[27] Lawrence W C M and Han G W 2006 Thermal fatigue behaviour of SiC/Al composite synthesized by metal infiltration Composites: Part A 37 1858–62

[28] Chen N, Zhang H, Gu M and Jin Y 2009 Effect of thermal cycling on the expansion of Al/SiC composite J. Mater. Process. Technol. 209 1471–76

[29] Huang Y D, Hort N and Kainer K U 2004 Thermal behaviour of short fiber reinforced AlSi12CuMgNi piston alloys Composites: Part A 35 249–63

[30] Hall W I and Patterson W G 1991 The effects of thermal cycling on the mechanical-properties of a SiCw/Al composite Scr. Mater. 25 805–10

[31] Sobczak J, Slawinski Z, Sobczak N, Darlak P, Asthana R and Rohatgi P 2002 Thermal fatigue resistance of discontinuously reinforced cast aluminium-matrix composites J. Mater. Eng. Perform. 11 395–602

[32] Huang Y D, Hort N, Deringa H, Maier P and Kainer K U 2006 Investigations on thermal fatigue of aluminium- and magnesium-alloy based composites Int. J. Fatigue 28 1399–405

[33] Herr A E, Canumalla S and Pangborn R N 1995 Thermal fatigue behaviour of squeeze cast, discontinuous alumina-silicate fiber-reinforced aluminium alloy (A356) composite Mater. Sci. Eng., A 200 181–91

[34] Prevey P S 1996 Current applications of x-ray diffraction residual stress measurement Lambda Technologies (OH: ASM International, Materials Park) 103–10