FATIGUE BEHAVIOUR OF AL-12% Si/SiC$_p$ COMPOSITE PRODUCED BY SQUEEZE CASTING TECHNIQUE

A.M.ABO EL-AINENE

Prod. Eng. & Mach. Design Dept., Faculty Of Engineering , Menoufia University Shebin El-Kom, Egypt.

ABSTRACT

In the present work, the fatigue behaviour of Al- 12% Si/SiC$_p$ composite containing (10% wt) SiC$_p$ particles have been compared with Al-12% Si alloy. Dislocation structure and microprocesses of fatigue crack initiation and propagation in the composite have been investigated using SEM and TEM. The cyclic stress response characteristics and fracture behaviour of the composite were also studied. The obtained results showed that the fatigue strength at 10^7 cycles of the composite is 105 MP$_a$, i.e. about 28.6% higher than matrix alloy. The voids and microcracks initiated at and near the interface between SiC$_p$ and matrix, where the higher density dislocations are presented, will propagate and link up to form the fatigue crack. Cyclic response of the composite revealed hardening to failure at all strain amplitudes. The fatigue fracture of the composite exhibits a macroscopically brittle characteristic at all strain amplitudes, but has local matrix ductility.

1. INTRODUCTION

The emergence of novel processing techniques coupled with the trend to lighter materials having specific strengths and stiffnesses has catalysed considerable scientific and technological interest in the development and use of numerous high-performance composites or hybrid materials as serious competitors to both the traditional and newer-generation monalithic alloys. The majority of such materials are metallic matrices reinforced with high-strength, high modulus, and often brittle, second phases in the form of fibers, particulates, whiskers and platelets, embedded in a ductile matrix.

Manuscript received from Dr: A. M. Abo El-Ainene **at: 12/7/1997,**
accepted at: 20/7/1997,
Engineering research bulletin, Vol. 21, No. 2, 1998,
Menoufiya University, Faculty of Engineering,
Shebin El- Kom, Egypt, ISSN. 1110-1180.

The reinforced metallic matrices offer the potential for significant improvements in structural efficiency, reliability, density, stiffness, strength (yield strength and ultimate tensile strength) and wear resistance over the monolithic counterpart while maintaining adequate levels of ductility and fracture toughness [1-10].

When the metal matrix composites are fabricated or annealed at a certain high temperature and cooled down to room temperature, plastic deformation is inevitable to take place in the matrix region near the interface because of the significant difference in thermal expansion coefficients between the reinforcement and the matrix. Therefore, numerous dislocations with high density are expected to exist in virgin specimens before cyclic straining. There is no doubt that the dislocations will have some effects on the fatigue damage and the cyclic straining will in turn act on them. It is generally believed that the interfaces between dissimilar materials are the sites for mechanical stress concentrations and often nucleate during the overall failure process.

Aluminium alloys reinforced discontinuously with SiC particles are receiving a great deal of attention from researchers and engineers, because the engineering properties of them have much less dependent on direction and the fabrication of them has an obvious advantage of saving costs. Therefore, applications of SiC_p composite materials to structural component of non-aerospace which demand low cost and specific gravity as well as good fatigue properties were being considered and realized. However, the mechanism of fatigue fracture and the relations between the fatigue behaviour and microstructure were not well studied although some interesting results have been publically reported [11-14].

So, it is the purpose of the present work to investigate fatigue behaviour and microprocesses of fatigue crack initiation in Al-12% Si alloy reinforced with (10% wt) SiC particles. This composite was fabricated by the squeeze casting technique. The effect of cyclic stress on dislocations and microstructure was also investigated for a better understanding of the failure process in the metal matrix materials. The Al- 12% Si alloy was chosen as a matrix for this study, because its widley used for load-bearing structural components as well as in the automotive industry.

2- MATERIALS AND EXPERIMENTAL PROCEDURE

Figure (1) presents the flow chart of the experiment. All the experimental procedures described in this section are referred to this chart.

2-1 Fabrication of Composite

In the present work, specimens of Al-12% Si alloy reinforced with (10% wt) SiC_p particles (size range 63-180 μm) were used. This composite was fabricated by the squeeze casting technique under a pressure of 60 MP_a during solidification for a duration of 120 second according to the procedure described in Refs. [10 & 15], and as shown schematically in Fig.(1). The composite was also solutionized at 520°C for 3 hrs., water quenched and then aged at 170 °C for 6 hrs.

2-2 Tensile Test

Flat tensile specimens of 3 mm thickness, 6 mm width and 24 mm gauge length (according to BS 1987 and ASTM E8-89b) were machined from the squeezed composite with the gauge length of specimens parallel to the longitudinal axis of the casting. Tensile testing at room temperature was conducted on a 20 ton universal testing M/C using constant cross-head speed of 3 mm/min.

2-3 Fatigue Tests

The fatigue specimens of 3 mm thickness, 8 mm width and 25 mm gauge length, were machined from the squeezed composite. The longest axis of each specimen was parallel to the longitudinal axis of the casting. Both sides of each specimen were carefully polished by conventional metallographic techniques to remove all scratches. Fatigue tests were conducted at room temperature on a push-pull fatigue testing machine at a frequency of 20 Hz. High-cycle fatigue tests were performed under constant load control, to determine the fatigue strength of the composite at 10^7 cycles. A sinusoidal waveform was used the controlling signals. The stress ratio (ratio of minimum stress to max. stress) $R = -1$ was selected. On the other hand, low-cycle fatigue tests were performed at a constant strain rate of 0.1% per second, to investigate the cyclic stress response characteristics and fracture behaviour of the composite.

2- 4 Metallographic Examination, SEM Fractography and TEM Fractography

The initial microstructure of the as-received composite material was characterized by optical microscopy after standard metallographic preparation techniques. Fracture surfaces of the deformed fatigue specimens were examined using Jeol scanning electron microscope to determine the predominant fracture mode and to characterize the fine scale topography of the fatigue fracture surface. In order to investigate the relationship between fatigue properties and microstructure, dislocation configuration of failed specimens were observed by transmission electron microscope, TEM.

3- EXPERIMENTAL RESULTS AND DISCUSSION

3-1 Microstructure

Figure (2) shows the photomicrograph of the structure in the as-cast condition. It is clear that, squeeze casting results in a dense structure with a grain refining effect. Also, the applied pressure achieves an uniform distribution of the hard ceramic phase (SiC_p) .

3-2 Fatigue properties

The fatigue test results are presented in Fig. (3), in which comparison of high cycle fatigue properties of two materials can be seen. It is apparent that the fatigue strength at 10^7 cycles of SiC_p reinforced Al-12% Si composite is 105 MP_a and increases by 28.6% compared with the matrix.

3-3 Cyclic Deformation and Microstructural Evaluation

The manner in which stress response varies with number of cycles and plastic strain amplitude is an important feature of the low cycle fatigue process. The stress response curves, which were determined by monitoring the stress response during total strain controlled fatigue, provide useful information on the cyclic and mechanical stability of the material . Mechanical stability of the intrinsic microstructural features during reverse plastic straining, and the ability of the material to distribute plastic strain over the entire grain volume are two important factors governing the cylic response of a material [16&17].

Figure (4) shows the variation of the stress amplitude ,σ, with the number of cycles, N, under different plastic strain amplitudes,ε. As shown the cyclic hardening was noticed in the initial stage of fatigue straining. With a continuous of cycling, the rate of hardening progressively diminished and the cyclic saturation was reached. The number of cycles at which the saturation begins to occur and the magnitude of the saturation stress depend strongly on the applied plastic strain amplitude. Fig. (5) shows a plot of the stress amplitude at saturation as a function of plastic strain amplitude provides the so called cyclic stress- strain curve behaviour of the composite Al- 12% Si/ SiC_p. From this figure it is clear that , the saturation stress- strain curve for SiC_p composite exhibits low strain hardening over the plastic strain region of $3x10^{-5}$ to $5x10^{-4}$. The occurance of this region is peculiar to the composite and this may be due to a continuous increase of the number of SiC_p/Al alloy interfaces involved in the cyclic deformation. As indicated later, the interface is the most significant dislocation source of cyclic deformation.

Figure (6) shows the dislocation arrangements in cyclic hardening stage of Al-12% Si/SiC_p. It is evident that the dislocations interact strongly with the interface which is not only the main dislocation source but also the main obstacle to dislocation motion. Fig. (7) shows TEM micrograph for fracture surface of fatigued specimen subjected to 190 MP_a cyclic stress about 8.8×10^4 cycles until failure occured . It is shown that much high density dislocation tangles and few precipitations appear at or near the SiC_p/ matrix interface and that high density dislocation networks are pinned by dispersed precipitation particles in the matrix. It is interesting to note that the isolated dislocation channel, where there are some curved screw dislocations appears at the corner region or near the interface of SiC_p/matrix and that the dislocation cells appear and precipitates extended due to the dislocation movement under fatigue load. At the same time, it is evident that dislocation meets a large particle and tend to bow round from the particle. It is demonstrated from the above observations that high density dislocation tangles and the channel are formed near SiC_p/ matrix interface as the result of the dislocations interacting strongly with precipitations and SiC particles and that the dislocation activity greatly increases at the interface and the corner of SiC_p, while the screw dislocation can easily move through the channel where the resistance is small. As a consequence of all the dislocation generation and movement, there is a possibility of void formation at the SiC_p/ matrix interface. Therefore, the channel will be associated with voids and microcrack at the interface between SiC_p and matrix.

3-4 SEM FRACTOGRAPHY

Figure (8) shows the morphology of fatigue crack formed on surface of Al- 12% Si/SiC_p composite. As shown, the cracks preferentially propagate along the path of aggregate SiC particles. Further microscopic observation reveals that the microcrack mainly initiates at or near the interface between SiC_p and matrix. Sometimes only few cracks cross the SiC particles.

Detailed SEM examinations were conducted also on the fatigue fracture surfaces of specimens. Typical fracture surface appearances are shown in Figs (9 & 10). Representative fractographs of the specimen deformed at total cyclic strain amplitude of 0.3% is shown in Fig.9 . The silicon carbide particles (SiC_p) were found in clusters throughout the fracture surface (Fig.9-a). High magnification observation revealed the presence of multiple cracks in the matrix region (Fig. 9-b). Shallow dimples were found distributed in the matrix. Assuming the intrinsic strength of each SiC particle is inversely proportional to the square root of its characteristics dimension, d_p, [18&19] :

$$\sigma_{SiCp} = \left[\pi E\, G_{pm} / 2(1-\nu^2) d_p\right]^{1/2}$$

where, E is the Young's modulus, ν is the poisson's ratio and G_{pm} is the effective fracture energy for dynamic propagation of the crack into the matrix. An increase in the tensile stress that occurs during cyclic hardening promotes microcrack initiation to occur at the particles. With continued cyclic deformation the cracks propagate into the ductile matrix. Numerous such microscopic crack causing a drop in load carrying capability of the specimen and culminating in fatigue failure. Furthermore, it is also possible that mismatch that exists between the brittle ceramic particles (SiC_p) and the ductile matrix (Al-12% Si) favors concentration of stress at and near the reinforcement particle causing the matrix in the immediate vicinity to fail prematurely or the particle to separate from the matrix (Fig.10). From the appearances of fatigue fracture surfaces it can be suggest that fatigue fracture of the Al-12% Si/SiC_p composite exhibits a macroscopically brittle characteristic, but on the microscal it is ductile .

All above mentioned results demonstrate that in the matrix near SiC_p/ matrix interface, high density dislocations which are instable state move and interact with the precipitations and SiC particles. Consequently, the dislocations are pinned and bowed to form Frank-Read sources which can emit a lot of dislocation loops. The loop can be piled at the interface (see Fig.7). As stress increases in this region the particular array of dipoles becomes instable, collapses and forms channel in which there is low resistance against dislocation movement reported by Laird [20]. These channels are then local weak spot of low flow stress where voids coalesce and promote crack initiation indicated by Chevalier et al. [21]. Obviously the channels in Al-12% Si/SiC_p composite display isolate feature and is located in the vicinity of interfaces, which can be distinguished from channels standing side by side in the conventional Al alloys revealed by Mitchell and Tear [22]. Therefore, it can be understood that fatigue crack initiation and propagation essentially occur in the vicinity of the interface even if the bond of interface is quite strong in the composite.

Finally, two factors can be considered to account for superior fatigue properties of Al-12% SiC_p composite in comparison with the matrix alloy. The first, it is well known that high dislocation density and small subgrain size in the matrix of the composite result in strengthening of the matrix and enhancing its strength level with which fatigue performance usually improves. Therefore, superior performance of high cyclic fatigue in the Al-12% Si/SiC_p composite could be attributed not only to the higher tensile strength of the reinforced materials but also to strengthening of the matrix by thermomechanical interacting. The second, the composite is subjected to low fatigue stress for long period, as a results of promoting second phases continuously such precipitating in the matrix such precipitates are always associated with the dislocations. Consequently, it is possible that high dislocations are pinned to enable the fatigue crack difficulty to form.

CONCLUSIONS

From this study, the following conclusions may be drawn :

1. In comparison with Al-12% Si alloy (matrix), the high cyclic fatigue strength at 10^7 cycles of the composite is superior by 28.6% .
2. The dislocation channels observed by TEM are only located in vicinity of the SiC_p/matrix interface and display isolated feature . It is indicated where voids will collect and microcracks initiate. Therefore, even if the bond between SiC_p and matrix is quite strong, the fatigue crack initiation and propagation will essentially generated in the matrix near interface.
3. Cyclic stress response of the composite revealed hardening to failure at all strain amplitudes.
4. The fatigue fracture of the composite exhibits a macroscopically brittle characteristic at all strain amplitudes, but has local matrix ductility.
5. The reasons for fatigue property improvement of the composite are essentially attributed to two factors. The first, higher strength level of the SiC reinforced particles and matrix strengthening by thermomechanical interaction. The second, the strengthening phases will be continuously precipitated for the fatigue process and then interacted with the high density dislocations. Consequently, dislocations pinned by the precipitations will move with difficulty and fatigue crack initiation be delayed.

REFERENCES

1. Lewandowski, J.J.,Liu, C., and Hunt, W.H., " Effects of Matrix Microstructure and Particle Clustering on Fracture of an Aluminium Metal Matrix Composite ", Mater. Sci., & Eng., Vol. 107A,(1989). PP.241-251.
2. Humphreys, F.J., "The Thermomechanical Processing of Al-SiC Particulate Composites", Mater. Sci., & Eng., Vol. 175 A,(1991), PP.267-273.
3. Ochiai, S., and Osamura, "K.,Influence of Matrix Ductility, Interfacial Bonding Strength and Fiber Volume Fraction on Strength of Metal Matrix Composites", Metall. Trans., Vol. 21A,(1990), PP.971-980.
4. Singh, P.,and Lewandowski, J.J.,"Effects of Heat Treatment and Reinforcement Size on Fracture During Tension Testing of a SiC_p Discontinuously Reinforced Aluminium Alloy", Metall. Trans.,Vol.24A, (1993), PP.2531-2543.
5. Strivatsan,T.S., Ibrahim, I.A.,Mohamed, F.A.,and Lavernia, E.J.,"Processing Techniques for Particulate - Reinforced Metal Matrix Composites", J.Mater. Sci., Vol.26,(1991), PP.5965-5978.
6. Stefanescu, D.M.,"Issues in Liquid Processing of Particulate Metal Matrix Composites", Key Eng. Materials, Vol. 79-80,(1993), PP.75-90.
7. Song, S.G., Vaidya, R.U., Zurek, A.K., and Gray, G.T., "Stacking Faults in SiC_p particles and their Effect on the Fracture Behaviour of a 15 Vol. Pct SiC/6061 Al-Matrix Composite", Metall. Trans., Vol. 27A, (1996), PP.549-465.

8. Young, H.S., and Chung, G.K., "The Effect of Applied pressure on Particle Dispersion Characteristics and Mechanical Properties in Metal- Stirring Squeeze - Cast SiC_p/Al Composites", J.Mater. Proc. Technol.,Vol.55, (1995), PP.370-379.
9. Roy,M.,Venkataraman,B.,Parasad,B.V.,Mahajan, Y.R., and Sundarajan,G., "The Effect of Particulate Reinforcement on the Sliding Wear Behaviour of Aluminium Matrix Composities", Acta Metall., Vol.23 A, (1992), PP.2833-2847.
10. Abou El-Ainene,A.M., and Taweel, T.A.,"Tribological Behaviour of Al-12% Si/SiC_p Composites", Eng. Res. Bull.,Faculty of Eng., Shebin El-Kom, Menoufia Univ., Vol. 18,(1995), PP.59-72.
11. Sugimura, Y., and Suresh, S.,"Effects of SiC Content on Fatigue Crack Growth in Aluminium Alloys Reinforced with SiC Particles", Metall. Trans., Vol. 23 A,(1992), PP.2231-2242.
12. Bonnen, J.J., Allison, J.E., and Jones, J.W.,"Fatigue Behaviour of 2 XXX Series Aluminium Alloy Reinforced with 15 Vol.% Silicon Carbide Particulates", Metall Trans., Vol. 22A,(1991), PP.1007-1019.
13. Kumai, S.,King, J.E., and Knott, J.F.,"Short and Long Fatigue Crack Growth in a SiC Reinforced Aluminium Alloy", Fatigue Fract.Eng. Mater. Struct., Vol.13, (1990), PP. 511-524.
14. Shang, J.K., and Ritchie, R.O., "Fatigue of Discontinuously Reinforced Metal Matrix Composites", in Metal-Ceramic Composites Eds R.J. Arsenault and R.K. Everett, Academic Press, Boston , MA, (1989), PP.255-285.
15. Khedr, O.M., Attia, A.N., and El-Desouky, A.R., "Squeeze Casting of Hybrid Silicon- 12% Aluminium Matrix Composites", 1st. Int. Symposium on Advances in Materials Science, Atomic Energy Authority, Egypt, March, 15-20, (1994).
16. Starke, E.A., and Lutjering, G.,"Cyclic Plastic Deformation and Microstructure", in Fatigue and Microstructure Ed. M.Meshi, ASM Int., Metal Park, Ohio, (1979), PP.205-235.
17. Srivatsan, T.S., and Coyne, E.J., " Micromechanisms Governing the Fatigue Behaviour of Aircraft Structural Alloys", Mater. Sci., Technol., Vol.5, (1989), PP. 548-556.
18. Lin, T., Evans , A.G., and Ritchie, R.O., " Stochastic Modeling of the Independent Roles of Particle Size and Grain Size in Transgranular Cleavage Fracture", Metall. Trans., Vol. 18A, (1987), PP. 641-650.
19. Lin, T., and Ritchie, R.O.," On the Effect of Sampling Volume on the Microscopic Cleavage Fracture Stress", Eng. Fract. Mech., Vol. 29, (1988), PP.697-703.
20. Laird, C.,"Fatigue and Microstructure Sponsored by ASM U.S.A., (1978), PP. 149-203.
21. Chevalier, J.L., Gibbons, D.F., and Leonard, L., " High Frequency Fatigue in Aluminium", J.Appl. Physics, Vol.43, (1972), PP.73-77.
22. Mitchell, A.B., and Teer, D.G., " Dislocation Structures in Aluminium Crystals Fatigued in Different Orientations", J.Metal Science, Vol.3, (1969), PP.183-189.

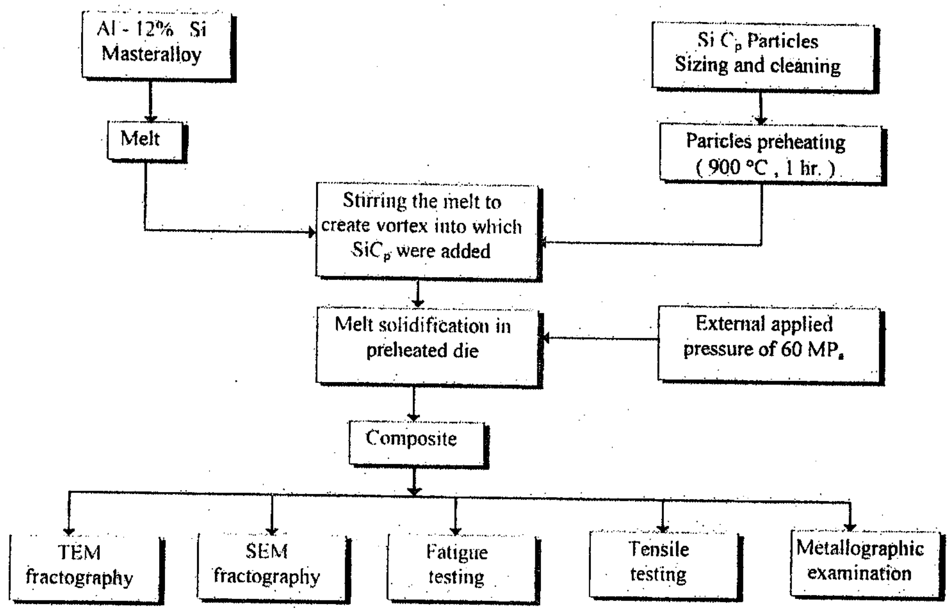

Fig. (1) Flow Chart of the experiment

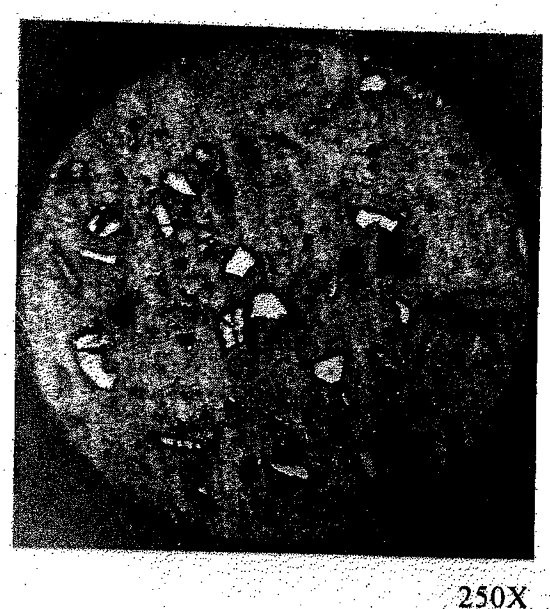

Fig.(2) Microstructure of the investgated composite.

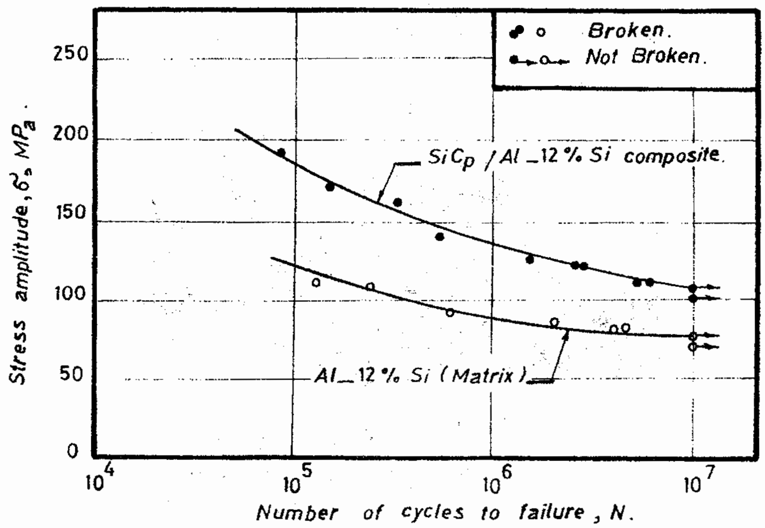

Fig (3) S_N Curves of Al_12 % Si alloy and SiC_p / Al _12 % Si composite.

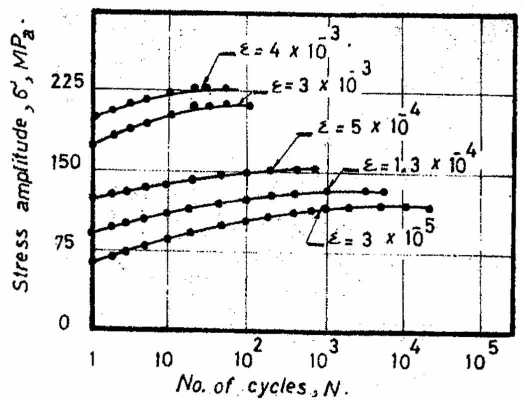

Fig.(4) Variation of the stress amplitude, б, with the No. of cycles, N, under different plastic strain amplitudes, ε.

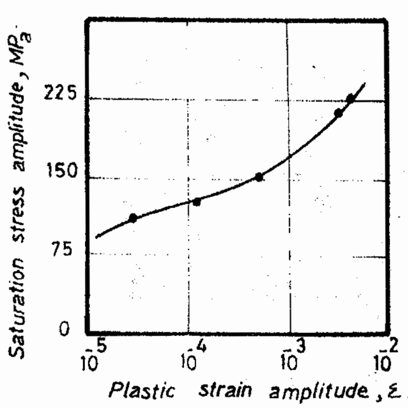

Fig.(5) Cyclic stress_strain curve for a Si C_p/ Al_12% Si composite.

Fig.(6) TEM micrograph showing the dislocation structures at the cyclic hardening stage in Al-12% Si/Si C_p composite ($\varepsilon = 1.3 \times 10^{-4}$).

Fig.(7) TEM micrograph showing the dislocation structure for fracture surface of fatigued specimen at $\sigma = 190$ MP_a .

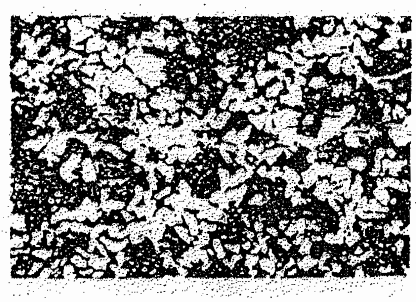

Fig.(8) SEM micrograph showing the fatigue crack propagation

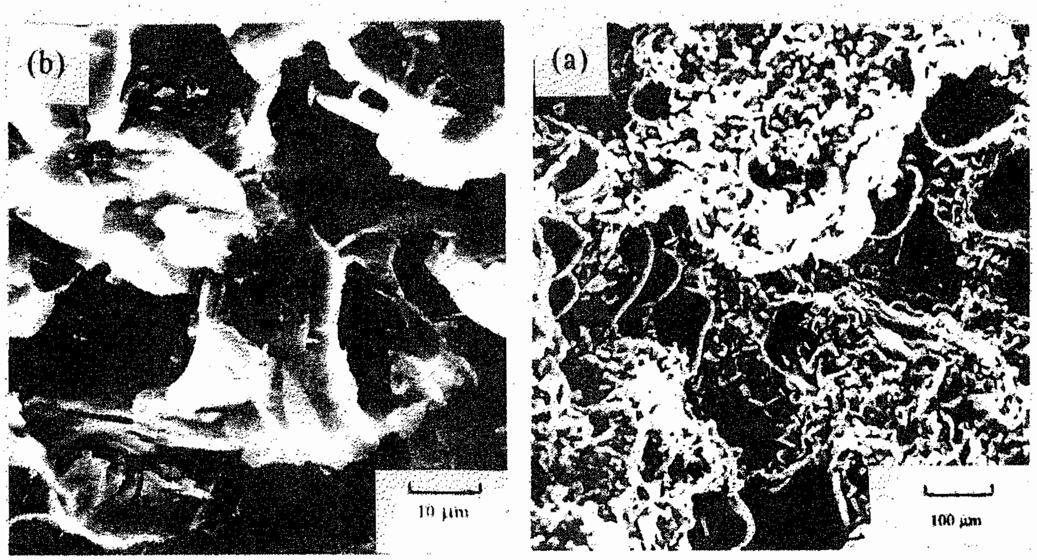

Fig.(9) SEM micrograph of the fatigue fracture surface of the composite specimen deformed at total cyclic strain amplitude of 0.3%.
(a) agglomerated mass of SiC particulates,
(b) cracking in the matrix .

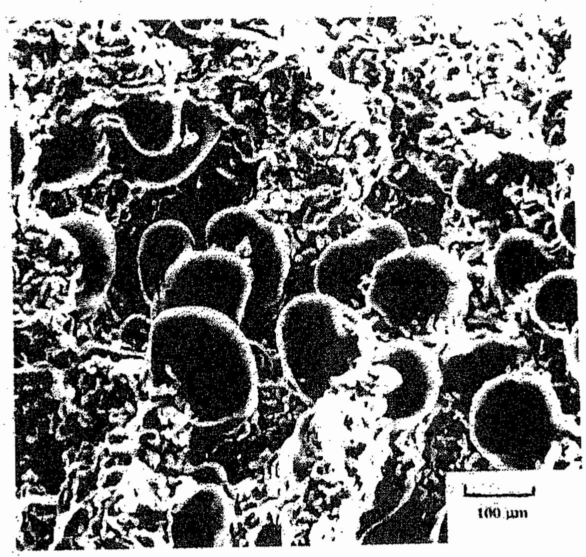

Fig.(10) SEM micrograph showing an agglomeration of SiC particulates on fatigue fracture surface of the transverse test

FATIGUE BEHAVIOUR OF Al-12%Si / Si C_p COMPOSITE PRODUCED BY SQUEEZE CASTING TECHNIQUE

سلوك الكلال لمؤتلفة الالومنيوم - ١٢٪ سليكون المعززة بحبيبات كربيد السليكون والمنتجة بأسلوب السباكة تحت ضغط"

د./ أحمد موسى أبو العينين
قسم هندسة الإنتاج والتصميم
كلية الهندسة والتكنولوجيا - جامعة المنوفية

الملخص العربي:

يهدف هذا البحث إلى دراسة سلوك الكلال لمؤتلفة سبيكة الألومنيوم - ١٢٪ سليكون المعززة بـ ١٠٪ حبيبات كربيد السليكون والمنتجة بأسلوب السباكة تحت ضغط (١٠٥ ميجابا سكال) .

اشتملت الدراسة في هذا البحث على إجراء إختبارات الشد الميكانيكية على بعض العينات لتعيين الخواص الميكانيكية لهذه المؤتلفة .كما تم استخدام الميكروسكوب الضوئي لدارسة التركيب البللوري وتوزيع الحبيبات داخل المؤتلفة .

وتم في هذا البحث إجراء كل من اختبارات الكلال High Cycle Fatigue (H.C.F), Low Cycle Fatigue (L.C.F) على ماكينة إختبار الكلال شد - ضغط مع ثبوت كل من الحمل المؤثر ومعدل الإنفعال على الترتيب . كما تم استخدام الميكروسكوب الماسح الالكتروني SEM لفحص سطح الكسر Fracture Surface للعينات المنهارة في اختبار الكلال واستخدم الميكروسكوب الالكتروني النفاذ TEM لفحص التغيرات التي تحدث في البنية البلورية وشكل الانخلاعات Dislocations للعينات المنهارة في اختبار الكلال .

ولقد خلصت الدراسة إلى عدة نتائج نوجزها في النقاط التالية :-

١ . تزايد مقاومة الكلال Fatigue Strength لهذه المؤتلفة بنسبة ٢٨,٦٪ مقارنة بسبيكة الألومنيوم - ١٢٪ سليكون (مادة البطانة Matrix) .

٢ . أظهرت نتائج الفحص باستخدام TEM ان مراحل شرخ الكلال Fatigue Crack المنشأ Initiation والنمو Propagation يكون من البطانة Matrix بالقرب من السطح البيني Interface بين البطانة وحبيبات كربيد السليكون (Hard Phase) .

٣ . الاجهادات الدورية Cyclic Stress Response تحدث (تسبب) تصليداً Hardening لهذه المؤتلفة حتى إنهيارها وذلك عند كل معدلات الانفعال التي تم تناولها بالدراسة .

٤ . أظهرت نتائج الفحص باستخدام SEM ان سطح الكسر للعينات المنهارة في اختبارات الكلال لهذه المؤتلفة يكون قصيفاً Brittle وذلك عند كل سعات الانفعال التي تم تناولها بالدراسة ، بينما موضعياً لدنا للبطانة Local Ductility .

٥ . أظهرت النتائج ان تحسن مقاومة الكلال لهذه المؤتلفة يعزو الى عاملين أولهما : ارتفاع مستوى المقاومة لحبيبات كربيد السليكون(Hard Phase) وتدعيم Strengthening البطانة بواسطة التأثير الميكانيكي الحراري Thermomechanical Interaction وثانياً : تأخر نشأة شرخ الكلال نتيجة للترسيب الذي يحدث للطور الصلد Hard phase أثناء تحميل الكلال مما يعيق من حركة الانخلاعات Dislocations.