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TENSILE PROPERTIES OF EXTRUDED $SiC_{(P)}$/Al-2124 BULK FUNCTIONALLY GRADED MATERIALS

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SUMMARY

Functionally graded materials (FGMs) are a new kind of composite materials whose composition and microstructure varied continuously or stepwise from place to place in ways designed to provide it with the necessary properties at the specific regions of the components. Bulk FGMs with radial graded cores based on the $SiC_{(p)}$/Al-2124 composite system fabricated by hot extrusion at 450 °C have high surface hardness because of the SiC particulate reinforced Al-2124 matrix annulus combined with high interior toughness due to the introduction of an unreinforced Al-2124 alloy central core. The tensile properties of bulk FGMs were elucidated in this study. The calculated and experimentally tensile results were compared. The results show that FGMs exhibit improved ductility but slightly lower 0.2% yield and tensile strength with respect to their conventional composite counterparts.

ÖZET

Fonksiyonel kademeli değişken malzemeler yeni bir kompozit malzeme türüdür. Bu malzemeler, bir makine parçasının belirli bölgelerinde istenilen bir özelliği elde etmek için dizayn edilmiş olup, malzemenin kimyasal birleşimi, mikroyapısı ya süreklilik arz edecek şekilde yada kademeli olarak makine parçasının bir bölgesinden diğer bir bölgesine doğru değişmesi söz konusudur. Bu çalışmada kullanılan fonksiyonel değişken malzemeler, birbiri içinde dairesel kademeli bir forma sahip olup $SiC_{(p)}$/Al-2124 kompozit sistemi esasına göre 400°C 'de sıcak ekstrüzyon ile üretilmişlerdir. Üretilen fonksiyonel değişken malzemelerin dış yüzeyi, Al-2124 matrix içine SiC parçacıklarının takviye edilmesinden dolayı oldukça sert, göbek kısmı ise takviyesiz Al-2124 alaşımından dolayı oldukça tok bir özellik gösterir. Bu çalışmada bu malzemelerin çekme mukavemeti özellikleri incelenmiştir. Elde edilen deneysel sonuçlar, teorik olarak geliştirilen formüllere göre hesaplanarak elde edilen sonuçlar ile karşılaştırılmıştır. Sonuç olarak, geleneksel kompozit malzemeler ile karşılaştırıldığında, fonksiyonel değişken malzemelerin sünekliğinin artmış olduğu fakat hafifçe % 0.2 akma ve çekme mukavemetlerinde azalmanın mevcut olduğu tespit edilmiştir.

I. INTRODUCTION

The highly demanding technological environment of the present age requires materials which can combine properties irreconcilable in common materials, e. g. high heat and corrosion resistance, high strength in elevated temperature applications, high wear resistance and high toughness. Achieving these different material property requirements at different positions in a component using conventional materials with homogeneous structure is not feasible. Functionally graded materials (FGMs) are a new kind of material that have a controlled progressive change in composition and structure across their sections. Therefore they can be designed to meet particular material property needs.

Functionally graded materials offer attractive advantages over their conventional counterparts, such as adjusted thermal mismatching [1], increased fracture toughness [2] and fatigue resistance [3], and graceful failure of FGMs [2].

Information may be found in the literature concerning the physical, particularly thermal, properties of FGMs [4], but there is a scarcity of data regarding mechanical performance, especially tensile strength. Therefore the present study is focused on the tensile properties of $SiC_{(p)}$/Al-2124 extruded bulk FGMs. These types of bulk FGMs have high surface hardness because of the SiC particle reinforced Al-2124 alloy matrix annulus combined with high interior toughness due to the introduction of an unreinforced Al-2124 central core. At the same time, some work on conventional extruded $SiC_{(p)}$/Al-2124 composites are also carried out for comparison purposes. The differences between the tensile properties of the composites and FGMs are discussed. The calculated and experimentally tensile results are compared.

II. EXPERIMENTAL PROCEDURE

Tensile testing was employed with two different model FGMs with radial graded cores specified as single core and double core FGMs. The central core of the single core FGM was unreinforced Al-2124 alloy which was surrounded by a SiC reinforced surface layer. The central core of the double core FGM was also unreinforced Al-2124 alloy, but an outer core having lower SiC volume fraction than that of the surface layer was introduced between the Al-2124 central core and the surface layer. Conventional $SiC_{(p)}$/Al-2124 composites were also carried out for comparison purposes.
Tensile specimens were machined from the steady-state sections of the extrudates according to E8M-93 specification. An Instron universal testing machine was employed with a crosshead speed of 0.1 mm/min. Load and displacement data recorded using a computer. Solution heat treatment (T4 temper) consisting of 500°C for 5h, followed by cold water-quenching was carried out on all specimens prior to tensile testing. The tensile strength was evaluated using the following equation:

$$\sigma = \frac{P}{A} \quad (1)$$

where; σ = tensile strength (MPa)
P = maximum load (MN)
A = the original cross-sectional area of the specimen (m^2)

III. RESULTS

The tensile properties for $SiC_{(p)}$/Al-2124 conventional composites and single and double core FGMs are summarised in Table 1. The yield strength is defined as the stress required for a plastic strain of 0.2 % because no clear yield point was obtained. The ductility is quoted in terms of percentage elongation of the test specimen.

The 0.2 % yield strength of composites increased with increasing SiC volume fraction up to and including 20 %SiC but decreased if the SiC content was further increased to 30 %. Similarly the yield strength of FGMs with a 30 %SiC surface layer

Table 1. Comparison of tensile properties of SiC particulate reinforced composites, single and double core FGMs.

SPECIMEN	Tensile Strength (MPa)	0.2% Yield Strength (MPa)	Elongation (%)	Code
Composites				
10 %$SiC_{(p)}$ / Al-2124	420 ± 10	290 ± 17	14.8 ± 1.1	
15 %$SiC_{(p)}$ / Al-2124	444.8 ± 15	315 ± 21	12.4 ± 1	
20 %$SiC_{(p)}$ / Al-2124	471.5 ± 9	343 ± 12	8.6 ± 0.8	
30 %$SiC_{(p)}$ / Al-2124	424.4 ± 18	320 ± 14	6.6 ± 1	
Single Core FGMs (Surface layer – Central core)				
20% $SiC_{(p)}$/Al 2124 – Al 2124	459.5 ± 8	330 ± 8	13.5 ± 0.7	20.Al.
30 %$SiC_{(p)}$/Al 2124 – Al 2124	400 ± 21	297 ± 8	10± 1.2	30.Al.
Double Core FGMs (Surface layer – Outer core – Central core)				
20 %$SiC_{(p)}$/Al 2124 - 10 %$SiC_{(p)}$/Al 2124 – Al-2124	440 ± 5	295 ± 13	17.3 ± 1.3	20.10.Al.
30 %$SiC_{(p)}$/Al 2124 - 15 %$SiC_{(p)}$/Al 2124 – Al-2124	395 ± 16	292 ± 9	13.3 ± 1.5	30.15.Al.

is less than those with 20 %SiC surface layers. When the 0.2 % yield strength of 20.Al. single core FGM (330 ±8 MPa) and 20.10.Al. double core FGM (295 ±16 MPa) are compared with that of 20 %$SiC_{(p)}$/Al-2124 composite (343 ±14 MPa), it can be seen that due to the introduction of outer and central cores, the single and double core FGMs show a 4 % and 16 % decrease in 0.2 % yield strength. The same phenomenon is observed for the 30.Al. single core FGM (297 ±8 MPa), the 30.15.Al. double core FGM (292 ±9 MPa) and 30 %$SiC_{(p)}$/Al-2124 composite (320 ±14 MPa).

The tensile strength values of composites increase with increasing SiC volume percentage up to 20 %SiC but then dramatically decrease with a further increase to 30 vol %SiC (Table 1). For example, the tensile strength of composites increases from 420 ±10 MPa to 471.5 ±18 MPa when the amount of SiC rises from 10 vol% to 20 vol%. In contrast, when the SiC content continues to increase to 30 vol%, there is a reduction in tensile strength to 424.4 ±18 MPa.

It was observed that single core FGMs have a slightly lower tensile strength as compared to the corresponding conventional composite counterparts. For instance, 20.Al. and 30.Al. single core FGMs exhibit ~3 % (459.5 ±8 MPa) and ~8 % (400±21 MPa) reduction in tensile strength, respectively, compared to 20 %$SiC_{(p)}$/Al-2124 (471.5±9 MPa) and 30 %$SiC_{(p)}$/Al-2124 (424.4 ±18 MPa) composites. This trend of reduction in tensile strength was also observed for 20.10.Al. and 30.15.Al. double core FGMs, as shown in Table 1.

The variation in ductility for composites and FGMs is also shown in Table 1 and as was anticipated, it can be seen that the introduction of SiC particles in the aluminium matrix alloy reduces the ductility of these materials. However in FGMs the addition of more ductile cores in the high level SiC composites, for example the introduction of an Al-2124 alloy core with 20 vol% or 30 vol% surface layers, and the introduction of both Al-2124 alloy central core and 15 vol% SiC outer core with 30 vol% SiC surface layer, resulted in a marked increase in their ductility compared with that of conventional composites. In the T4 temper, the ductility increases from the value of 8.6±0.8 % elongation for 20 %$SiC_{(p)}$/Al-2124 composites to 13.5±0.7 % and 17.3±13 % for 20.Al. single core and 20.10.Al. double core FGMs, respectively. The same phenomenon was also observed with 30 %$SiC_{(p)}$/Al-2124 composite (6.6±1 %) and 30.Al. single core (10±1.2 %) or 30.15.Al. double core (13.3±1.5 %) FGMs.

IV. DISCUSSION

Based on results obtained in the present study, it can be stated that 0.2 % yield strength and tensile strength of the $SiC_{(p)}$/Al-2124 composites increase with increasing SiC volume fraction up to 20 vol%SiC but decrease if the SiC content is further increased to 30 vol% (Table 1).

Several different mechanisms of strengthening have been proposed in the literature to explain the strength of the SiC reinforced metal matrix composites. These mechanisms are summarised as follows: 1) the transfer of load from the aluminium alloy matrix to the SiC particles, 2) residual stress occurs in the aluminium alloy matrix and plastic strains are introduced near the SiC particles because of the difference in coefficients of thermal expansion (CTE) between SiC particles and ductile aluminium alloy matrix. The dislocation density is thus enhanced in the aluminium alloy matrix due to the presence of the hard and brittle SiC particles, 3) strengthening enhancement from constrained plastic flow in the aluminium alloy matrix. SiC particles can resist the plastic flow of the ductile matrix, so an average internal stress in the matrix is generated, 4) strengthening arising from inherent strengths of the reinforcement and matrix in the composite as per the rule of mixtures theory [5,6,7,8].

It is assumed that the major contribution to strength of the $SiC_{(p)}$/Al-2124 composite is the high dislocation density generated due to mismatch in thermal coefficient of expansion between SiC particles and Al alloy matrix. The $SiC_{(p)}$/Al-2124 composite has a large CTE mismatch strain, the plastic deformation-induced dislocations would become dominant when the plastic strain exceeds the thermal mismatch strain. Dislocation generation due to CTE mismatch in the metal matrix composites has been confirmed by several investigators [9].

In the present case, when the SiC volume fraction exceeds 20 %, a slight decrease in 0.2 % yield strength (~ 6 %) was observed. This is in good agreement with Lin's study [10]. He attributed this to the increasing amounts of agglomeration and poor consolidation as the silicon carbide volume fraction increased. Therefore the anticipated strengthening effect of the high SiC content addition would be degraded and result in a less pronounced improvement in the strength. FGMs exhibit lower 0.2 % yield strength as compared with their corresponding composite counterparts. This is due to the bulk average SiC content of the FGMs being less than that of the composite material.

It is agreed that reduced tensile strength for the high the composites fail prematurely before they achieve their maximum strength due to defects such as SiC agglomerates. It has been widely reported that clustering of the reinforcement offers preferential sites for void or crack initiation and causes a degradation in the overall strength of composites [11]. In addition, it was observed in this work, and previously reported by Lin [10], that when the SiC content exceeds 20 vol%, the agglomeration of SiC particles increases and this results in a lower strength than expected for a homogeneous distribution. Furthermore it has been established that an enhanced dislocation density is generated in the matrix during the plastic deformation and due to the presence of the SiC particles. It becomes progressively more difficult to relieve the resulting local stress concentrations as the SiC content increases. Thus, tensile and yield strengths may decrease at high SiC contents because the local stresses around the SiC particles are high enough to initiate failure before the composite's potential strength is achieved.

Other studies based on the $SiC_{(P)}$/Al-2124 composite system also demonstrated an increase in 0.2 % yield strength and tensile strength as compared with that of Al-2124 alloy base matrix in the T4 condition, as summarised in Table 2. It should be noted that there are differences in the data for SiC/Al-2124 composite in the same heat treatment condition (T4) obtained by different SiC volume fraction is attributable to the fact that investigators, but there is a general trend of an increase in strength with increase in volume fraction, but the data are not uniformly consistent. The major causes of the differences in the data reported for nominally the same composites include: SiC particle size differences, lack of reproducibility from batch to batch, the amount of hot working, different fabrication temperatures and the fabrication of different shapes, such as rod, plate, etc.

The tensile strength of FGMs is proportional to the area fraction of the layer and cores. This will be discussed further in terms of a comparison of calculated and experimentally measured results. It is believed that all the above mentioned factors which affect the composite strength will also play a role in determining the properties in FGMs. The tensile strength of an FGM may be slightly less than the corresponding composite depending on the SiC content, but the ductility of the FGMs is superior to that of composites.

The 0.2 % yield strength and tensile strength of both single and double core FGMs were predicted using a simple rule of mixtures approach. The SiC reinforced constituent layer/core data of Table 1 were utilised to calculate the predicted strength of FGMs. The yield strength and tensile strength of unreinforced Al-2124 alloy in the T4 condition were taken from the reference of You et al. [12

Table 2. Comparison of tensile properties of some SiC particulate reinforced composites and their base matrix alloys available in the literature.

MATERIALS	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation (%)	References
MATRIX ALLOYS				
Al-2124 (T4)	518	374	11	Lin [10]
"	491	327	18	Srivatsan et al. [11]
"	450	296	22	You et al. [12]
COMPOSITES				
10 %$SiC_{(p)}$/Al-2124-T4	547	440	4.5	Lin [10]
17.8 %$SiC_{(p)}$/Al-2124-T4	610	400		Lloyd [13]
20 %$SiC_{(p)}$/Al-2124-T4	495	450	2	Lin [10]
"	537	351	10.5	Srivatsan et al. [11]
"	560	405	----	Lloyd [13]
"	606	436	4.7	You et al. [12]
"	552	400	7	Harrigan [14]
30 %$SiC_{(p)}$/Al2124-T4	543	387	5.2	Srivatsan et al. [11]
"	593	441	4.5	Harrigan [14]

given in Table 2. In terms of the rule of mixtures theory, the 0.2 % yield strength and tensile strength of FGMs depend on the area fraction of each layer/core in the material, thus the 0.2 % yield strength and tensile strength of FGMs are given by the following expressions :

$$\sigma_{FGM}^{0.2\% YS} = \sigma_{layer\,1}^{0.2\% YS}\frac{A_{layer\,1}}{A_{FGM}} + \sigma_{layer\,2}^{0.2\% YS}\frac{A_{layer\,2}}{A_{FGM}} + \ldots + \sigma_{layer(n)}^{0.2\% YS}\frac{A_{layer(n)}}{A_{FGM}} \quad (2)$$

$$\sigma_{FGM}^{TS} = \sigma_{layer\,1}^{TS}\frac{A_{layer\,1}}{A_{FGM}} + \sigma_{layer\,2}^{TS}\frac{A_{layer\,2}}{A_{FGM}} + \ldots + \sigma_{layer(n)}^{TS}\frac{A_{layer(n)}}{A_{FGM}} \quad (3)$$

where;

$\sigma_{FGM}^{0.2\% YS}$ = the 0.2 % yield strength of FGM

$\sigma_{layer\,1}^{0.2\% YS}, \ldots, \sigma_{layer(n))}^{0.2\% YS}$ = the 0.2 % yield strength of each constituent layer/core in FGM

σ_{FGM}^{TS} = the tensile strength of FGM

$\sigma_{layer\,1}^{TS}, \ldots, \sigma_{layer(n)}^{TS}$ = the tensile stress of each constituent layer/core in FGM

$\left(\frac{A_{layer\,1}}{A_{FGM}}\right), \ldots, \left(\frac{A_{layer(n)}}{A_{FGM}}\right)$ = the area fraction of each constituent layer/core

The calculated and experimental 0.2 % yield strength and tensile strength of FGMs with different SiC volume fraction are compared in Figures 1 and 2, respectively. The calculated 0.2 % yield strength values are within 20 % of the experimental values for 20 %SiC and 30 %SiC series, except for the 30.15.Al. double core FGM which is within 25 %. The tensile strength values calculated using a simple rule of mixtures approach are generally within 2 % of the experimental values for the 20 %SiC series. The percentage differences between calculated and experimental values for the 30 %SiC series are higher than for the 20 %SiC series. While the 20 %SiC series FGMs exhibits very good agreement between experimental and calculated values, the 30 %SiC series demonstrate a poor level of agreement. This indicates that when the SiC volume fraction of the surface layer exceeds 20 vol%, the increasing amounts of agglomeration, porosity, poor consolidation and delamination

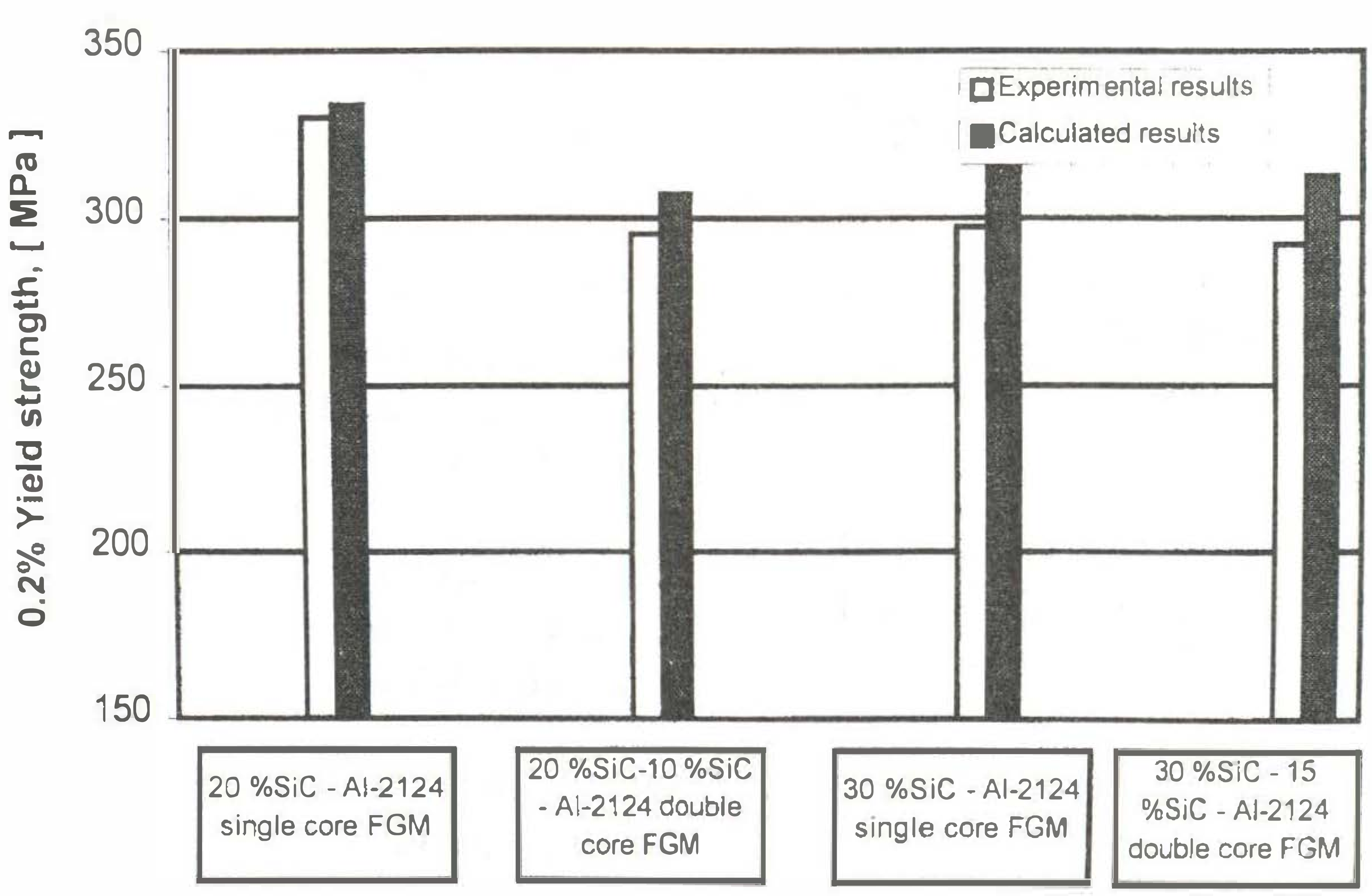

Figure 1. Comparison of experimental and calculated 0.2 % yield strength results for FGMs.

between layers or cores have a significant effect on the mechanical performance of FGM specimens. Also, it can be assumed from the calculated tensile strength values for single core FGMs, for example 20.Al. single core FGM, that as the 20 %SiC surface layer breaks, the Al-2124 central core cannot support the total transferred load, and the FGM exhibits a catastrophic failure in a similar manner to the 20 %$SiC_{(p)}$ /Al-2124 conventional composite.

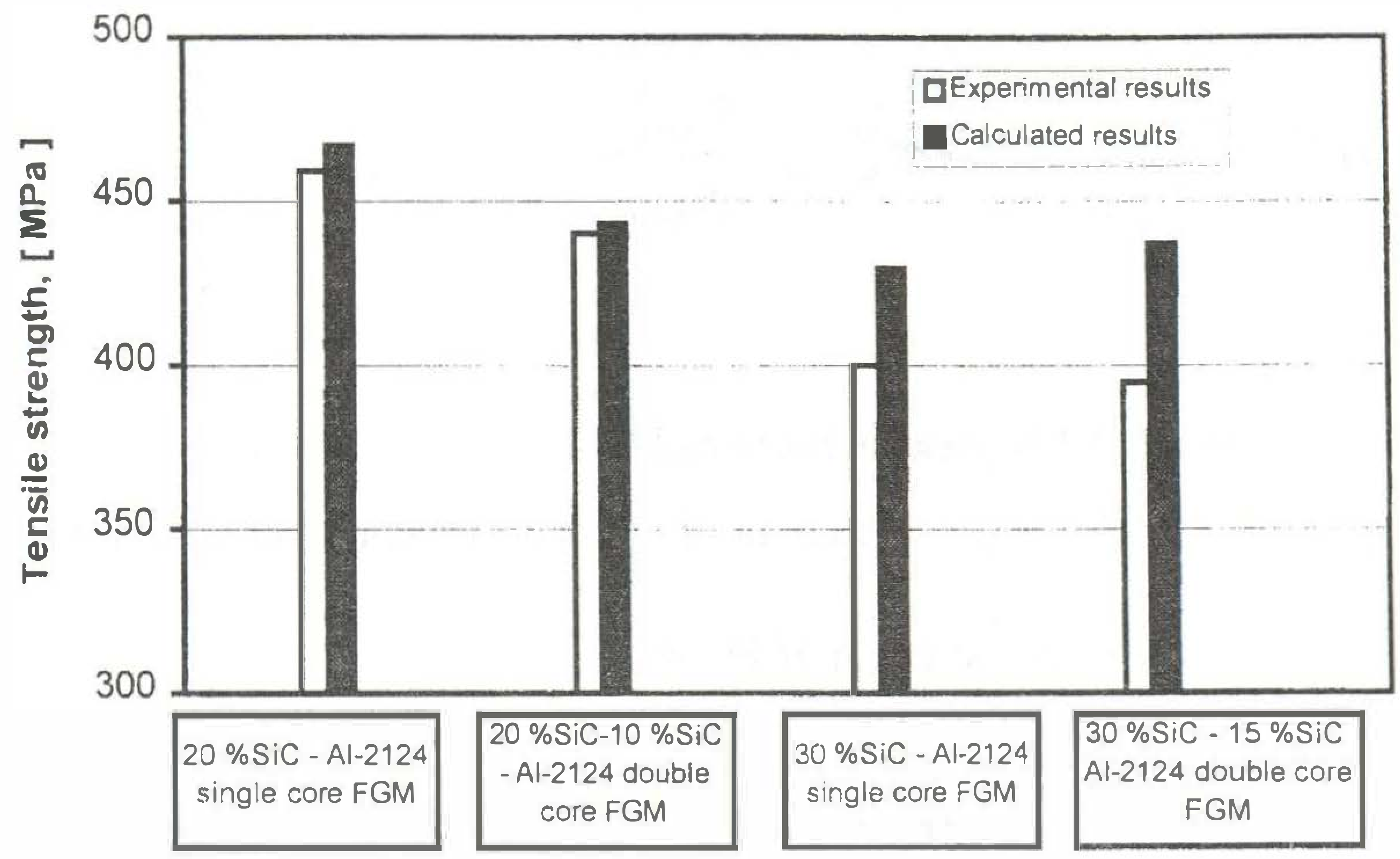

Figure 2. Comparison of experimental and calculated tensile strength results for FGMs.

V. CONCLUSIONS

This investigation has shown that the fabrication of the $SiC_{(p)}$/Al-2124 bulk FGMs can provide beneficial effects on tensile properties. These FGMs show improved ductility due to the introduction of cores of unreinforced and/or lower SiC reinforced content but slightly lower 0.2% yield and tensile strengths with respect to their conventional composite counterparts.

REFERENCES

[1] Rawlings, R.D., 1995, "Tailoring properties: Functionally Graded Materials", Materials World, Vol. 3, No. 10, pp. 474-475.

[2] Imergy, J.A., 1996, "Fracture Behaviour of 2124 Al- SiC Functionally Graded Materials", PhD thesis, Imperial College of Science, Tech. and Medicine, London.

[3] Uzun, H., 1998, "Fabrication and Mechanical Properties of $SiC_{(p)}$/Al-2124 Functionally Garded Materials" PhD thesis, Imperial College of Science, Tech. and Medicine, London.

[4] Kumakawa, A., Sasaki, M., Maeda, S. and Adachi, H., 1990, "Fabrication and properties of functionally gradient materials", J. Jpn. Soc. Powder Metall., 37, (2), pp. 313-316.

[5] Zok, F., Jansson, S., Evans, A.G., Wardone, V., "The mechanical behaviour of a hybrid metal matrix composite", 1991, Metallurgical Trans. A, Vol. 22A, pp 2107-2117.

[6] Flom, Y., Arsenault, R.J., 1986, "Deformation of SiC/Al composites", Journal of Metals, pp. 31-34.

[7] Arsenault, R.J., Fisher, R.M., 1983, "Microstructure of fiber and particulate SiC in 6061 Al compositess", Scripta Metall., Vol 17, pp. 67-71.

[8] Kim, Y-H., Lee, S., Kim, N.J., Cho, K.,1994, "Effect of microstructure on tensile and fracture behaviour of cast A356Al/SiC_p composite", Vol 31, No 12, pp. 1629-1634.

[9] Davidso, D.L., 1991, "Tensile deformation and fracture toughness of 2014 + 15 vol Pct SiC particulate composite", Metall. Trans. A, Vol 22A, pp. 113-123.

[10] Lin, C-Y, 1994, "Fabrication and properties of fonctionally graded materials", Ph.D. Thesis, Imperial College, London.

[11] Lewanski, J.J., Liu, C., Hunt, W.H., 1988, Processing and Properties for Powder Metallurgy Composites, Eds. P. Kumar, K. Vedula, A. Ritter, pp.117-125.

[12] You, C.P., Dollar, M., Thompson, A.W., Bernstein, I.M., 1991, Metall. Trans. A, Vol. 22A, pp. 2445-2455.

[13] Lloyd, D.J., 1994, Int. Metal. Rew., 39, 1, pp.1-12.

[14] Harrigan, W.C., 1987, DWA Composite Specialities, Inc., Engineered Materials Handbook, pp. 50-85, ASM International.