A 2-D finite element model to show the effect of shape and orientation of porosity on the mechanical properties of particle reinforced metal matrix composites

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Abstract

The effect of shape and orientation of porosity on the mechanical properties of particle reinforced metal matrix composites has been studied in the present work. The effect of different shapes of pores on the Young's modulus of elasticity and yield strength of the metal matrix composites have been studied with the help of a 2D finite element model. It has been established that shape and orientation of porosity dominates the mechanical properties of the composites.

Keywords: Porosity, Metal Matrix Composites, FEM, Modulus of Elasticity, Young's Modulus

Introduction:

The synthesis of metal matrix composites either by liquid metallurgy or powder metallurgy results in unavoidable porosity contents. In stir-casting reinforcing ceramic particles like alumina or silicon carbide are added to molten metal or alloy while stirring by an impeller. The ceramic particles have generally poor wettability with molten metals and alloys, and so, transfer of these particles into the melt poses considerable difficulty. Addition of suitable wetting agents to the melt often promotes wettability by promoting chemical reaction at the surface of the particles. Stirring the melt with a stirrer while the particles are added to the melt, results in suction of the particles through the vortex at the centre below the stirrer along with bubbles. Particles are often surrounded by the bubbles in order to avoid melt-ceramic surface contact which has higher energy compared to the surface energy of the ceramic particles. These bubble particle combine because of their density may remain within the melt without bubble floating out and particle segregating to the bottom by settling. Thus, the composite ingot made by the casting the slurry containing bubble-particle combines has porosity. A second source of porosity is enhanced dissolution of gases from the environment during stirring which exposes fresh metal to the surface of the melt continuously to dissolve gases from the environment. Lower solubility of gases in solid metal causes evolution of gases during solidification. The surface of ceramic particles often favorable sites for heterogeneous nucleation of bubbles resulting in the second source of bubble-particle combines in the mould giving rise to another source of porosity. Thus, porosity in cast composites is quite natural unless additional measures are taken during processing which adds to its cost.

Porosity causes deterioration in mechanical properties of the composites. The presence of porosity is observed to lower the strength of a composite almost linearly. Therefore, it is necessary to investigate the influence of porosity on the mechanical properties like modulus and strength so as to be certain that the advantage gained by reinforcing with particles are not lost due to additional porosity. The formation of porosity and its effect on mechanical properties of MMCs have been the subject of several experimental studies. It is generally accepted that tensile properties decrease with increasing porosity content. Since the porosity cannot be tailor made in a sample, a detailed understanding of the effect of size, shape and orientation has to be undertaken through theoretical studies. In the present study, a 2D finite element study has been undertaken to develop an understanding of the effect of porosity on the mechanical properties of the particle reinforced metal matrix composites. The effects of volume fraction as well as the type of porosity on the Young's modulus and yield strength have been the focus of the current study.

Modeling

A two dimensional FEM model is constructed with a square area having an edge length of 5 mm. This area is meshed with plane, four node square elements with an edge length of 50 µm. Thus the whole model consists of 10,000 elements. Out of these elements 10,000*V_f^v (V_f^v is the volume fraction of the porosity) are randomly selected with the help of a computer program and are removed from the element list as these elements represent porosity. Again, 10,000*V_f^p elements are randomly selected from the list of the remaining elements with the help of computer program (V_f^p is the particle volume fraction in the composite) and are assigned particle properties. The remaining elements are assigned matrix properties. These particle and matrix elements are randomly distributed over the mesh. The effective global composite properties are determined on the basis of average elemental stress-strain relationship obtained through this model.

Results and discussion

Nonlinear analysis has been performed to predict the effect of porosity on the yield strength. Nonlinear analysis is performed with four different types of pores represented by 1*1, 1*4, 2*2 and 4*1 in the present study. The notation m*n represents the area of pore introduced by the removal of (m x n) elements where m represents the length of m grid elements in X direction and n similarly represents the length n grid elements in Y direction. Thus, 1*4 and 4*1 represent pores elongated respectively in Y and X directions with aspect ratios of 1:4 and 4:1 but having the same area as the square pore represented by 2*2 which has aspect ration of unity. For each size and shape of the pore, the pores are randomly distributed in a composite containing 30 volume percent of particles but for three different porosity contents of 2.5, 5.0 and 7.5 volume percents. For the nonlinear analysis, the edge of the composite at Y=0 is kept fixed but that at Y=5 mm is subjected to uniform displacement u_y=.01 mm to give a maximum strain of .002. This displacement is applied in 20 steps and the results for each step are noted. The average elemental stresses and strains in Y direction for each step are plotted to show the nonlinear behavior of the composite. Fig. 1 shows the nonlinear behavior of the composites with 2.5 volume percent porosity for different pore types. It is observed that smaller size of porosity as in 1*1 causes relatively less damage to load bearing capacity in the material. Material with 2*2 pores have stress–strain curve lower than that having the same volume fraction of 1*1 pores. The most damaging feature appears to be elongation of pores transverse to the loading direction as evident from the lowest stress-strain curve for 4*1 pores, even lower than 2*2 pores of the same area. It is interesting to note that the stress-strain curve for a material with 1*4 pores is higher than that containing 2*2 pores which have a higher length in the transverse direction to loading. So it is the size of the pores, its aspect ratio and orientation with respect to loading direction, which together determine the stress-strain curve for the material containing porosity.

On the basis of the stress-strain curve, the modulus of elasticity and the yield stress in Y direction (loading direction) are obtained for materials containing different pore types as shown in Figs. 2 and 3 respectively. The stress at the point where the tangent to the elastic behaviour portion crosses the tangent to the plastic behaviour portion in a particular stress-strain curve is considered as the yield stress for that particular stress-strain behaviour. The yield stress determined with this method gives the most conservative value of the yield stress. It is clear from these figures that the modulus of elasticity as well as yield strength is dominated by pore type to the great extent. These results show that for 7.5 porosity volume percentages the yield strength of a composite with 30 particle volume percentages is reduced from 77 MPa to 47.8 MPa when the pore type changes from 1*4 to 4*1, which are the least and most damaging pore types in a material containing the same volume fraction of pores. Thus, there could be 38% reduction in the yield strength depending on the shape size and orientation of pores for the same

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porosity volume percentages. Similarly for the elastic modulus, there could be 33% reduction when the porosity type changes from 1*4 to 4*1 for 7.5 volume percent of porosity. These results also show that for the same porosity type (type 1*4) the reduction in the modulus of elasticity is only 5.3% when the porosity volume percentages are increased from 2.5 to 5.Also the results for yield strength show that there is only 9% reduction in the yield stress for the same porosity type (type1*4) when the porosity volume percentages are increased from 2.5 to 5.These results clearly indicate the dominance of the porosity type on the mechanical properties of the composites.

Conclusions

The present work presents a simple 2D FEM model is to predict the effect of porosity on the mechanical properties of particle reinforced metal matrix composites. It suggests that the yield strength as well as modulus of elasticity decreases with increase in porosity. It also predicts the effect of porosity size on the mechanical properties of the composites. It predicts that the average porosity content is not a reliable parameter to predict the mechanical properties. The effect of large pore area perpendicular to the loading direction is more effective than the overall porosity content. The results of the present model are in agreement with the available models and experimental results.

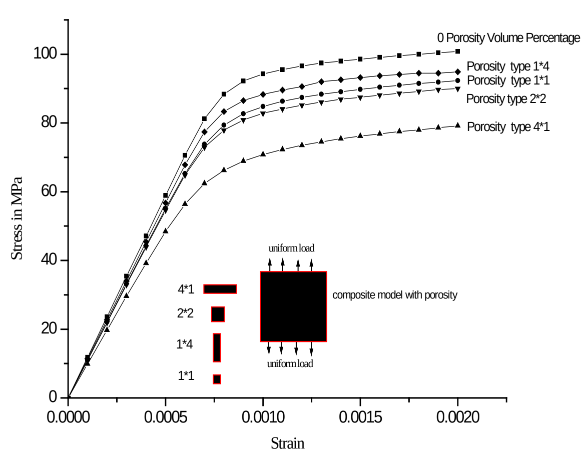

Fig.1 Nonlinear stress-strain behavior of a composite with 30 vol% randomly distributed particles and 2.5 vol% porosity of different sizes and aspect ratios.

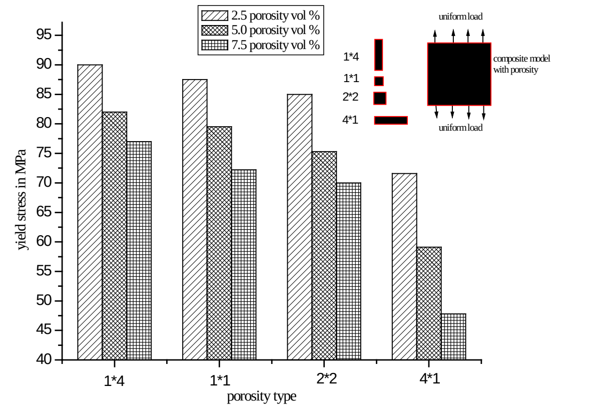

Fig.2 Effect of porosity type on the yield strength of the composite with randomly distributed particles (30 particle volume percentages).

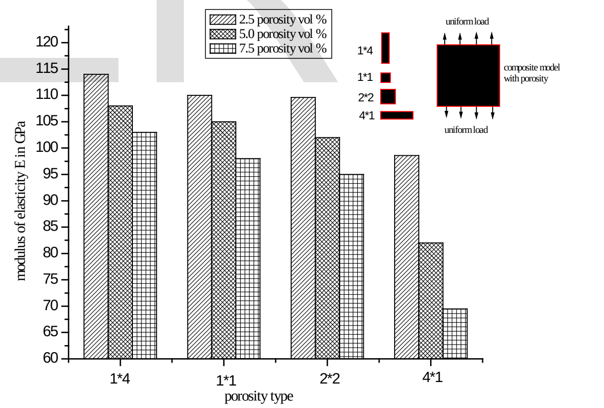

Fig.3 Effect of porosity type on modulus of elasticity of the composite with randomly distributed particles (30 particle volume percentages).

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