สิ่งตีพิมพ์ปริทัศน์ของผลของตัวเสริมความแข็งแรงแบบอนุภาคบนพฤติกรรมการแปรรูปของวัสดุเชิงประกอบที่มีโลหะเป็นเนื้อหลักพร้อมด้วยเทคนิคที่ใช้ในการทำแบบจำลอง

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บทคัดย่อ

ในบทความนี้ สิ่งตีพิมพ์ต่างๆ ที่เกี่ยวข้องกับอิทธิพลของตัวแปรของตัวเสริมความแข็งแรงหลายชนิด อาทิเช่น รูปร่าง, ขนาด, อัตราส่วนเชิงปริมาตรของตัวเสริมความแข็งแรงต่อเนื้อโลหะหลัก, การกระจายตัวและปรับตัวตามทิศทาง โดยเฉพาะอย่างยิ่งต่อการเปลี่ยนแปลงรูปร่างของวัสดุเชิงประกอบที่มีโลหะเป็นเนื้อหลักโดยถูกเสริมความแข็งแรงด้วยอนุภาคเซรามิกส์ ได้ถูกเขียนเป็นบทปริทัศน์ ความสำคัญของพื้นผิวรอยต่อระหว่างตัวเสริมความแข็งแรงกับเนื้อโลหะก็ได้ถูกบันทึกด้วยเทคนิคการทำแบบจำลองไฟไนต์เอลิเมนต์เชิงกลในระดับอนุภาคโดยการใช้ยูนิตเซลล์ (ซึ่งใช้งานโดยทั่วไปสำหรับการสืบสวนผลของตัวแปรของอนุภาคเสริมความแข็งแรงนี้) บนพฤติกรรมของวัสดุเชิงประกอบดังกล่าวข้างต้นระหว่างการแปรรูป ได้ถูกสำรวจและรวบรวม

พบว่าการเติมอนุภาคเสริมความแข็งแรงลงในโลหะผสมเนื้อเดียวเป็นการปรับปรุงความแข็งแรงและความแข็งเกร็งของวัสดุเชิงประกอบให้ดีขึ้นแต่ความยืดหยุ่นจะลดลง นอกจากนี้ตัวเสริมความแข็งแรงยังทำให้เกิดลักษณะความไม่เป็นเนื้อเดียวกันต่อโลหะผสม ดังนั้นเป็นสาเหตุให้เกิดสนามความเค้นและความเครียด (ขึ้นกับตำแหน่งของพื้นผิวรอยต่ออย่างมาก) ขึ้นระหว่างได้รับภาระเชิงกล ซึ่งเป็นอิทธิพลจากตัวแปรของตัวเสริมความแข็งแรง สำหรับวัสดุเชิงประกอบดังกล่าว ผลการเกาะรวมกลุ่มของอนุภาคไม่ได้แสดงบทบาทที่สำคัญสำหรับการมีอิทธิพลต่อความแข็งแรงและความยืดหยุ่นที่ถูกทำนาย โดยเฉพาะอย่างยิ่งเมื่ออัตราส่วนเชิงปริมาตรของตัวเสริมความแข็งแรงต่อเนื้อโลหะหลักมีค่าต่ำ สำหรับมุมมองด้านการวิเคราะห์เชิงตัวเลขถึงแม้ว่ารูปแบบสมการแบบ 3 มิติสามารถให้วิธีการที่เที่ยงตรงมากสุดสำหรับการทำแบบจำลองยูนิตเซลล์ แต่ค่าทำนายที่ได้รับโดยใช้การวิเคราะห์แบบ 2 มิติก็อยู่ในลักษณะสอดคล้องอย่างสมเหตุสมผลกับข้อมูลจากการทดลอง

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A Review of Particulate Reinforcement Effects on Its MMCs Deformation Behaviour with Modelling Techniques

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Abstract

In this paper, publications related to the influences of the various reinforcement factors, in particular, of particulate-reinforced metal matrix composites (PRMMCs), such as, its shape, size, volume fraction, distribution and orientation, on the deformation are reviewed. The importance of the reinforcement-matrix interface is also noted. Micromechanical finite element (FE) modelling techniques using unit cells employed for investigating these effects on the behaviour of such composites during deformation are surveyed.

It has been found that the addition of rigid reinforcing particles within monolithic metal alloys improves their strength and stiffness, but the ductility is reduced. The reinforcement also introduces inhomogeneity to the metal alloy, thus causing highly localized stress and strain fields to be set up during mechanical loading, influenced its factors of reinforcement. For PRMMCs, the effect of reinforcement clustering does not play a significant role in influencing the predicted strength and ductility, especially at low reinforcement volume fractions.

For the viewpoint of numerical analyses, although full three-dimensional formulations can provide the most accurate method for the modelling of the unit cell, but the predictions obtained by use of two-dimensional analysis are in reasonable qualitative agreement with the experimental data.

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1. Introduction

Metal matrix composites (MMCs) are a broad family of materials aimed at achieving an enhanced combination of properties. The addition of a ceramic reinforcement phase in monolithic metal alloys significantly alters their mechanical and physical properties, as well as deformation behaviour [1]. With proper control, this alteration can be exploited to increase the performance of metal alloys. To date, the attainment of higher strength and stiffness has been the prime motive behind the development of MMCs [2]. Other important improvements in parameters, such as density, wear resistance, thermal expansion and resistance to high temperatures, can be achieved by suitable selection of reinforcements and metallic matrices. At the same time, the desirable properties of metal alloys such as workability, ductility, and high thermal and electrical conductivities should preferably be maintained [2][3]. Furthermore, the desired combination of properties needs to be obtained at lowest cost.

Particulate-reinforced metal matrix composites (PRMMCs) are one class of MMCs. They generally comprise of a ductile metallic alloy reinforced with a hard ceramic reinforcing material in the form of particles by a variety of sizes and shapes. As most PRMMCs consist of constituents not at equilibrium with each other, there is clearly potential for matrix-reinforcement reactions to occur [1][3]. Control of such reactions and the avoidance of reinforcement degradation during the production and application of these materials are of great importance.

In order to achieve a better basic understanding of PRMMCs both in macroscopic and microscopic levels, it is therefore beneficial to summarise the findings of researchers in the subsequent section, especially those related directly to the influence of the reinforcing phase on the deformation behaviour of materials, when subjected to applied loads. Factors, namely, the shape, size, volume fraction, distribution and orientation of the reinforcing particles, have been examined. The importance of the reinforcement-matrix interface has also been considered. Additionally, finite element (FE) modelling techniques through the use of *unit cell* approach, which are customarily employed to investigate the microscopic deformation of the PRMMCs, are included and highlighted.

2. Effects of Reinforcing Particles on Metal Matrix Composites

The effects of factors such as its shape, size, volume fraction, distribution and orientation of the reinforcements on the deformation behaviour of the PRMMCs are discussed and summed up briefly in subsections below. Particular attention is paid to Al-SiC particulate-reinforced system. However, it is thought that the influence of various factors considered is generally applicable to other systems of MMCs as well, as the basic strengthening mechanism involved is the same.

2.1 Effects of Reinforcement Shape

Results from uniaxial tensile tests on cylindrical specimens of Al-SiC MMCs conducted by McDanels [4] and Papazian and Adler [5] have shown that different types of reinforcement shape lead to different strengths for the MMCs. Numerical analyses using the FE method were carried out by Bao *et al.* (1991) [6] and Llorca *et al.* [7] on unit cells for PRMMC materials consisting of a matrix cylinder containing a single reinforcement. The predictions agree with the experimental observations mentioned.

The reason for the difference in strength between different types of reinforcement is that different reinforcement shapes provide different levels of localised constraint to plastic flow of the matrix, thus giving rise to different levels of localised hydrostatic (triaxial) stresses within the matrix, especially at the reinforcement-matrix interface. This has been revealed by the numerical studies by Bao *et al.* [6] and Llorca *et al.* [7]. Profile irregularities at the reinforcement-matrix interfaces, such as sharp corners, tend to increase the constraint to plastic flow and, hence, increase the level of triaxial stresses locally. Because higher load is required to cause plastic flow locally, the overall strength of the MMCs increases.

It has been found that for a given reinforcement volume fraction the ultimate strength of the MMCs increases with increasing reinforcement aspect ratio [1].

2.2 Effects of Reinforcement Size

The size of the particulate reinforcement varies considerably. A typical mean diameter is approximately 3-10 μm. For PRMMCs, both two-dimensional (Christman *et al.* [8]) and three-dimensional (Levy and Papazian [9]) FE analyses on unit cell models have confirmed that the size of the reinforcing phase affects the overall strength of this class of composites.

Experiments using uniaxial tensile tests, carried out by Kamat *et al.* [10], Flom and Arsenault [11], Brechet *et al.* [12] and Doel *et al.* [13], have demonstrated that the overall strength of MMCs increases with increasing particle size up to a critical level. However, beyond that it starts to decrease as the reinforcement size further increases. A possible reason for this is that large reinforcements may increase the likelihood of reinforcement fracture at relatively low levels of strain. This results in the decrease of the strength once the critical size has been exceeded.

2.3 Effects of Reinforcement Volume Fraction

Both experimental investigations and FE analyses have revealed that the overall strength of MMC materials is strongly affected by the volume fraction of the reinforcement. Uniaxial tensile tests, conducted on aluminium matrix composite specimens reinforced with nodule or particulate type of reinforcement by McDanels [4], have shown that an increase in the volume fraction of the reinforcement always enhances the stiffness (Young's modulus) as well as the ultimate strength of the MMCs, regardless of the type of reinforcement. Similar observations were also made in uniaxial tensile tests carried out by Papazian and Adler[5] on an Al-SiC MMC (with whisker or particulate reinforcements) and Kamat *et al.* [10] on a particulate-reinforced Al-Al_2O_3 MMC.

Results obtained from FE analysis agree with those obtained from experiments. Bao *et al.* [6], Llorca *et al.* [7], Christman *et al.* [8] and McHugh *et al.* [14] have all shown the strong dependency of the overall strength on the volume fraction of the reinforcement.

2.4 Effects of Reinforcement Distribution

Scanning electron microscopy (SEM) photographs obtained by McDanels [4] and optical micrographs attained by Llorca *et al.* [7] have indicated that the distribution of reinforcing particles in PRMMCs is highly random. Furthermore, high concentration regions (clustering) of reinforcement tend to exist in PRMMCs.

FE analysis of PRMMCs using the unit cell approach assumes an orderly and periodic arrangement of reinforcement within the PRMMC. Llorca *et al.* [7], Christman *et al.* [8] and McHugh *et al.* [14][15] have found that the distribution of particulate reinforcement does not alter the predicted overall strength of PRMMCs. This finding is essential for validating the approach of FE unit cell modelling of PRMMCs as it justifies the assumption of regular distribution of particles made in modelling such PRMMCs. However, Llorca *et al.* [7] have pointed out that the effect of reinforcement distribution on the overall strength of PRMMCs may become significant at high volume fraction of the reinforcement and also in whisker or short fibre-reinforced MMCs. In these cases, the clustering effect may result in significant error in modelling when compared with experiments.

2.5 Effects of Reinforcement Orientation

Sorensen *et al.* [16] and Mammoli and Bush [17] have adopted a three-dimensional FE unit cell approach and investigated the effects of reinforcement orientation on both elastic and plastic behaviours under tension of an Al-SiC composite system. In their models, the Al-alloy matrix is characterised as elastic-viscoplastic with isotropic hardening, while the SiC reinforcement is assumed to be isotropic and remain elastic. Perfect bonding between the matrix and the reinforcement is also assumed.

For the whisker-reinforced composites, the results from numerical analyses of the two research groups referred above confirm the significant influences of the reinforcement orientation even at relatively low volume fractions. They revealed a strong decrease in tensile strength for small deviations of the whiskers from perfect alignment with the axis of applied uniaxial stress. When the misalignment is sufficiently large, however, the tensile stress-strain response becomes rather insensitive to the precise value of the misalignment angle. In comparison with the experimental data by Sorensen *et al.* [16] on a similar composite subjected to tension at various angles to the whisker axis, good agreement and the same trends have been found. It is obvious that orientation of the reinforcement plays a significant part only if the aspect ratio of the reinforcement is high [16].

On the other hand, the computed overall tensile stresses for the case of composites reinforced by particles show much lower sensitivity to the reinforcement alignment. Nevertheless, even for particles having aspect ratio around unity such as flat-ended cylinder, cube and rectangular parallelepiped in shape, there still is a noticeable effect of particle orientation [16][18]. Clearly, if spherical particles had been considered, there would be no influence of orientation. Bao *et al.* [6] have shown that unit aspect ratio cylinders result in a higher average stress level than other ones with the same volume fraction of spherical particles.

2.6 Significance of Reinforcement-Matrix Interface

The presence of the second phase reinforcement complicates the microscopic behaviour of MMCs during the deformation process. FE analysis shows that high triaxial stress concentrations arise at the interfaces when the MMC is subjected to macroscopically uniform stresses. This has been confirmed by the results from three-dimensional FE analysis by Levy and Papazian [9] and Hom [19]. Llorca *et al.* [7], Christman *et al.* [8] and McHugh *et al.* [14] also made similar observations for PRMMCs.

Additionally, profile irregularities at the interfaces such as sharp edges and corners tend to increase the level of triaxiality locally at these positions, thus altering the overall behaviour of the material. The profile irregularities also cause high equivalent plastic strains to be generated locally, as demonstrated in Llorca *et al.* [7], Christman *et al.* [8] and Hom [19]. The high triaxial stresses and equivalent plastic strains increase the likelihood of damage initiation by void formation and debonding, which then affects the load-bearing capacity of the MMC material.

Hence, the reinforcement-matrix interfaces in MMCs are often the potential locations for the initiation of damage. The behaviour of these interfaces must be studied carefully and understood before the overall properties of MMCs can be controlled precisely.

3. Techniques Employed in Modelling Micromechanical Behaviour of PRMMCs

Through the review of existing literature in the previous section, it has been shown that the mechanical properties, such as stiffness, hardening characteristics and strength, of PRMMCs are all significantly affected by the reinforcing phase in composites. Thus, it is useful to be able to model the effects of the reinforcement on the behaviour of PRMMCs, so that studies can be conducted on various properties of such materials.

Since the reinforcing mechanism of the particles is at the microscopic level, a detailed investigation of the micromechanical behaviour of the MMC material is required in order to achieve understanding at this level. The unit cell approach is becoming popular, in particular, in conjunction with finite elements (FE) in order to obtain in-depth understanding of the performance of these advanced materials. This numerical scheme allows the influence of the various factors of the reinforcement to be studied systematically, and also endorses the development of the local stress and strain fields within the composite during deformation.

3.1 Modelling Techniques

Numerical analyses of plastic deformation of PRMMCs are often performed using the FE method. In most common approaches, it is assumed that the reinforcing particles in the MMC are arranged periodically. Two general types of periodic arrangement are often used: the square and the hexagonal arrangement [6][8], as shown in Fig. 1 (a) and (b).

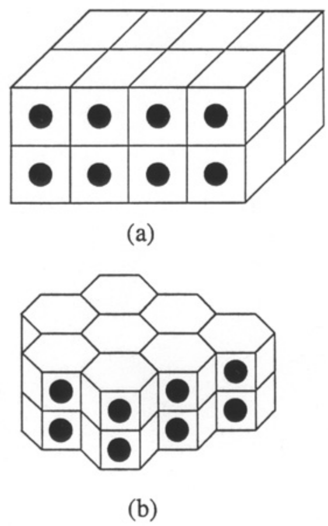

Fig. 1 Periodic inclusion packing arrangement often used in micromechanical investigations of PRMMCs (a) cubic and (b) hexagonal

For PRMMCs, analyses have been performed on a single unit cell, which consists of one reinforcing particle embedded in a hexagonal cylinder of matrix material and the MMC material is assumed to be made up of a series of such unit cells. Two-dimensional analyses are often used after the unit cell is approximated by a circular cylinder. The cross sections of the PRMMC in horizontal and vertical planes are then schematically represented in Fig. 2. In addition, Tvergaard [20] has indicated that by using an axisymmetric formulation, the circular cylinders can be considered as an approximation to the three-dimensional array of hexagonal cylinders. However, the periodic arrangement assumption requires the vertical side of the cylinder to remain straight and vertical during deformation in order that displacement compatibility between adjacent unit cells is maintained. The imposition of this constraint is usually achieved by ensuring that the total traction on the side is zero during deformation [7][8].

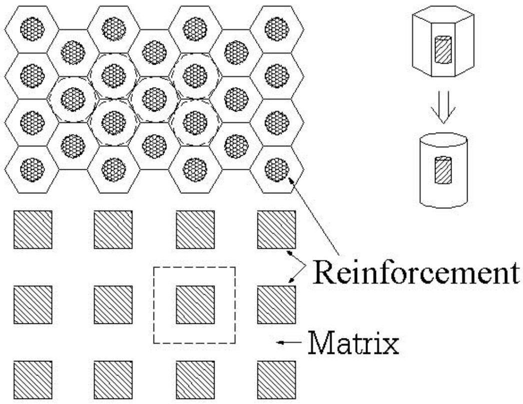

Fig. 2 The axisymmetric unit cell for modelling PRMMCs

For PRMMCs, the reinforcement is customarily represented either by sphere or by unit cylinder whose length and radius are equal. A numerical study using the unit cylinder to represent the reinforcement by Christman *et al.* [8] showed that this type of reinforcement offered better predicted stress-strain behaviour than the one that represents the reinforcement by sphere. The unit cylindrical reinforcement type can be considered as a better representation of true PRMMCs, because it has been shown experimentally that true reinforcing particles often contain sharp edges as opposed to being smooth and spherical in shape (see for example McDanels [4], and Flom and Arsenault [11]). The volume fraction of the unit cell used in the modelling is usually assumed to be the same as the composite.

The use of two-dimensional axisymmetric formulations for the unit cell can avoid the need for a full three-dimensional analysis, and the predictions obtained are found to be in reasonable qualitative agreement with the experimental data, although for the whisker-reinforced types, the agreement is poor [7][8]. Full three-dimensional formulations provide the most accurate method for the modelling of the unit cell and have been adopted by some researchers such as Levy *et al.* [9] and Hom [19].

The major assumption made to enable the FE modelling of PRMMCs is that the reinforcement is arranged in a periodical manner. Under this condition, it tends to over-predict the strength and stiffness, and under-predict the ductility of the composites [7][8]. To improve in these respects, attempts have been made by researchers to take into account of the random distribution and the clustering of the reinforcement phase within a MMC. Christman *et al.* [8] used the plane strain formulation to model a cell containing more than one reinforcement, and arranged them in such a way so that different degrees of reinforcement clustering can be achieved. It can give a good qualitative study of the effect of clustering on the overall behaviour of the MMC material. Llorca *et al.* [7] also employed the same approach when studying the effect of clustering on the overall ductility of the MMC. In both accounts [7][8], it has been found that for whisker-reinforced MMCs, clustering of the reinforcement tends to lower the predicted overall strength, and increases the predicted ductility of the composites. This means that the FE prediction can be made to agree with the experimental data better, by including the effect of clustering in modelling. For particulate reinforcement types, however, they have found that the effect of reinforcement clustering on the prediction (overall strength and ductility) is less significant, especially at low volume fraction of reinforcement ($<10\%$).

Another important point revealed through the unit cell approach is that the aspect ratio of the unit cell influences the predicted results, as indicated by Christman *et al.* [8]. Since the aspect ratio of the unit cell used represents the distance between adjacent reinforcing particles within a MMC, it should be carefully selected, so that the unit cell represents the MMC as close as possible. However, it is difficult to determine this in experiments and, hence most of the numerical analyses mentioned above use an arbitrarily chosen value. Normally, the aspect ratio for the unit cell is assumed to be the same as those for the reinforcement [6][8].

McHugh *et al.* [14] have proposed and applied a completely different approach for modelling the deformation behaviour of a PRMMC. Instead of the usual unit cell approach, the MMC has been modelled using microstructural analysis. The kinematics behaviour of a single deforming crystal has been used to derive a set of constitutive equations that describe the deformation of the crystal. A polycrystalline model can then be constructed, by assuming it as an assembly of a series of single crystals or grains. The MMC model is subsequently obtained by assuming purely elastic behaviour for certain grains within the polycrystal in a systematic manner. With this approach, the microscopic behaviour of the composites has been modelled in detail.

4. Conclusions

In this paper, a review of the effects of factors of reinforcement, such as its shape, size, volume fraction, distribution and orientation on both the macroscopic and microscopic behaviour of PRMMCs has been made. Meanwhile, a survey has been carried out of the development of various typical FE unit cell modelling techniques often employed to predict the effective stress-strain relationship in elastic-plastic regime and overall stiffness and/or strength under applied loads.

From observations obtained experimentally and computationally, they have shown that the strengths of PRMMCs are directly dependent upon different shapes of reinforcement due to providing different levels of localised constraint to plastic flow of the matrix. In addition, it has also been found that the overall strength of such composites increases with increasing particle size up to a critical level. The stiffness as well as the ultimate strength of PRMMCs is always enhanced by an increase in the volume fraction of the reinforcement. Generally, the distribution of particulate reinforcement does not alter the overall strength of this composite type. However, this effect may become significant at high reinforcement volume fractions. It is a fact that composites reinforced by particles show much lower sensitivity to the reinforcement alignment than others. Due to the reinforcement-matrix interfaces are often the potential locations for the initiation of damage, then the behaviour of these interfaces must be studied carefully before the overall properties of PRMMCs can be controlled precisely.

The FE numerical scheme is the common tool used to model the deformation behaviour of the PRMMCs. It allows the influence of the various reinforcement factors to be studied systematically, and also allows detailed investigation of the development of the local stress and strain fields within the PRMMC during deformation. Two-dimensional plane strain and axisymmetric, as well as three-dimensional analyses have been employed.

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