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# EFFECTS OF HOT-ROLLING PROCESSES ON THE FRACTURE BEHAVIORS AND MECHANICAL PROPERTIES OF 2009Al/SiCp METAL MATRIX COMPOSITES

## VPLIV PROCESA VROČEGA VALJANJA NA MEHANSKE LASTNOSTI IN NAČIN LOMA KOMPOZITOV S KOVINSKO MATRICO VRSTE Al 2009 OJAČANEGA Z DELCI Al/SiC

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Defects such as pores and weak interfacial bonding in SiC-reinforced aluminum-matrix composites (AMCs) limit the reinforcement effect. The objective of this study is to control the microstructural defects and status of the Al/SiC interface in an 2009Al/SiCp composite using rolling processes. The influence of the rolling reduction rate on the microstructure and mechanical properties is investigated. The fracture behavior of the 2009Al/SiCp composite is observed through *in-situ* scanning-electron-microscopy tensile tests. The results demonstrate that an appropriate rolling reduction rate can effectively eliminate microstructural defects in the matrix and enhance the interfacial bonding strength of Al/SiC. Plastic deformation during the rolling processes expands the dislocation-strengthening regions near the Al/SiC interface. Consequently, mechanical loads can be more efficiently transferred from the aluminum matrices to SiC particles. In the as-sintered specimens, cracks primarily initiate at the Al/SiC interfaces during tensile tests. In contrast, cracks predominantly propagate from the SiC particles to Al matrices in the as-rolled specimens. This work provides a fundamental understanding of the dynamic changes in the microstructure and the resulting mechanical properties during hot rolling of SiC-reinforced AMCs.

Keywords: aluminum matrix composite, rolling process, microstructure evolution, fracture behavior, *in-situ* tensile test

Napake kot so pore, razpoke in slaba medfazna mikro vezava na mejah z SiC delci ojačanimi kompoziti z matrico na osnovi Al zlitine (AMCs; angl.: aluminum matrix composites) zmanjšujejo učinek ojačitve. Avtorji v tem članku opisujejo študijo kontrole mikrostrukturnih napak in stanje medfaznih mej med matrico iz zlitine vrste Al 2009 in delci SiC (2009Al/SiCp) med procesom vročega valjanja. Avtorji so raziskovali vpliv stopnje redukcije valjanja (med 30 % in 90 %) na mikrostrukturo in mehanske lastnosti izbranega kompozita. Obnašanje in potek loma 2009Al/SiCp kompozita so avtorji opazovali *in-situ* med nateznim preizkusom skozi vrstični elektronski mikroskop (SEM). Rezultati so pokazali, da pravilno izbrana redukcija valjanja učinkovito odpravi vpliv mikrostrukturnih napak v matrici in izboljša mejno vezavno trdnost med matrico iz Al zlitine in SiC delci. Plastična deformacija med procesom valjanja širi področja utrditve zaradi povečane koncentracije dislokacij na mejah med matrico 2009Al in SiC delci. Posledično se mehanske obremenitve med valjanjem bolj učinko prenašajo s kovinske matrice na SiC delce. Na sintranih vzorcih se razpoke med nateznim preizkusom primarno začnejo na mejah med 2009Al in SiC delci. Nasprotno pa med vročim valjanjem razpoke prednostno napredujejo z SiC delcev na 2009Al matrico. Ta raziskava po mnenju avtorjev omogoča temeljno razumevanje dinamičnih sprememb mikrostrukture in posledično spremembo mehanskih lastnosti med procesom vročega valjanja kompozita z izbrano matrico iz Al zlitine ojačano z delci SiC.

Ključne besede: kompoziti z matrico iz Al zlitine, proces vročega valjanja, razvoj mikrostrukture, potek loma, *in-situ* natezni preizkus

## 1 INTRODUCTION

Al/SiC composite materials are widely used in the aerospace, automotive, and electronics industries due to their preferable properties such as high specific strength and good wear resistance.[1–3] Rolling is a commonly used method for fabricating thin strips of Al/SiC composites. It has been demonstrated that plastic deformation can improve the microstructure and homogenize the distribution of the reinforcement particles in AMCs.[4–6] Meanwhile, plastic forming can heal the defects in AMCs and improve the interfacial bonding strength between the reinforcement particles and metal matrices, resulting in an increase in the overall strength of the AMCs. However, the rolling of particle-reinforced AMCs remains challenging due to poor plasticity and a narrow processing window caused by the uncoordinated deformation between hard reinforcing phases and matrices.

Rolling processes of particle-reinforced AMCs have been studied to optimize the microstructure and enhance the overall strength.[7–10] A study by A. El-Sabbagh et al.[11] investigated the hot rolling behavior of stir-cast parti-

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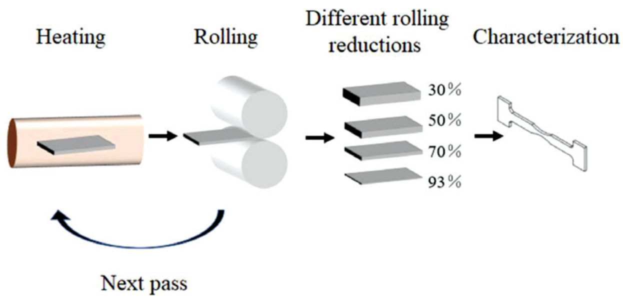


**Figure 1:** Schematic of the rolling process

cle-reinforced AMCs and found that there is a "critical rolling reduction rate" in a rolling process. If the applied reduction rate during rolling exceeds the critical rolling reduction rate, it leads to cracking at the edges of particle-reinforced AMCs, making it difficult to fabricate thin strips of particle-reinforced AMCs. Jin-feng NIE et al.[12] prepared Al-TiB2/TiC *in-situ* composites using the *in-situ* reaction, and then the composites were subjected to subsequent hot rolling with an increasing reduction rate. The experiment substantially increased the material strength by continuously applying rolling deformation. Jiang et al.[13] used a combination of powder metallurgy and hot rolling to incorporate Gd and B4C particles into a 6061Al matrix, and this study showed a significant increase in the tensile strength of the composite. Xiaopu Li et al.[14] sintered AA6061-SiC composites with plasma and performed multi-pass hot rolling. The results showed that the dislocation density in the matrix was high after rolling, while the SiC particles exhibited good distribution after rolling.

In summary, AMCs show a high cracking tendency in rolling processes due to the presence of reinforcement particles, and the forming ability is more sensitive to the processing parameters compared with matrix metals.[15] Hence, it is difficult to apply large deformation to AMCs in rolling, making the fabrication of thin AMC strips challenging.

To address the fabrication of 2009Al/SiCp thin strips, this paper investigates the influence of the cumulative reduction rate on the microstructure and performance of 2009Al/SiCp composites during a rolling process. The microstructure characterization and tensile properties of the as-rolled materials are carried out, and SEM *in-situ* tensile tests are used to observe the fracture behavior of 2009Al/SiCp. By establishing the "process-microstructure-performance" relationship, the study provides fundamental guidance for the rolling of AMC thin strips.

## 2 EXPERIMENTAL PART

In this study, 2009Al/15.vol%SiCp composites prepared with hot isostatic pressing (Jiangxi Baohang New Materials Co. Ltd.) were utilized as the raw materials, with an average SiC-particle size of 15 µm. The chemical composition of the material is shown in **Table 1**.

**Table 1:** Chemical composition of 2009Al/SiCp matrix

| Element | Si | Fe | Cu | Mn | Mg | Cr | Ti | Al |
|---|---|---|---|---|---|---|---|---|
| Content (*w*/%) | 0.1 | 0.2 | 3.6 | 0.1 | 1.0 | 0.1 | 0.1 | Bal. |

As shown in **Figure 1**, the as-sintered 2009Al/SiCp composites with an initial size of (30 × 40 × 3) mm were subjected to hot rolling using a two-high mill for multiple passes. The rolls had a diameter of 250 mm. The samples were heated to 510 °C for 10 min in a tubular resistance furnace. The reduction for each pass was set as 0.05–0.3 mm. The final thickness of the as-rolled samples was approximately 0.1–0.2 mm.

To investigate the distribution of SiC and the microstructure of the metal matrix, the metallographic structure of the as-rolled specimens was observed using a scanning electron microscope (SEM).[16] The sample size was (8 × 10) mm, and the surface was observed along the normal direction-rolling direction (ND-RD). Diamond polishing was performed on the samples, followed by eroding the Al grain boundaries using a 0.5 % hydrofluoric acid aqueous solution for 15 s.

As shown in **Figure 2**, a JOEL-IT500 SEM and an *in-situ* tensile-test bench were demployed to observe the microstructure and fracture behaviors of the materials. The mechanical properties of the materials with different

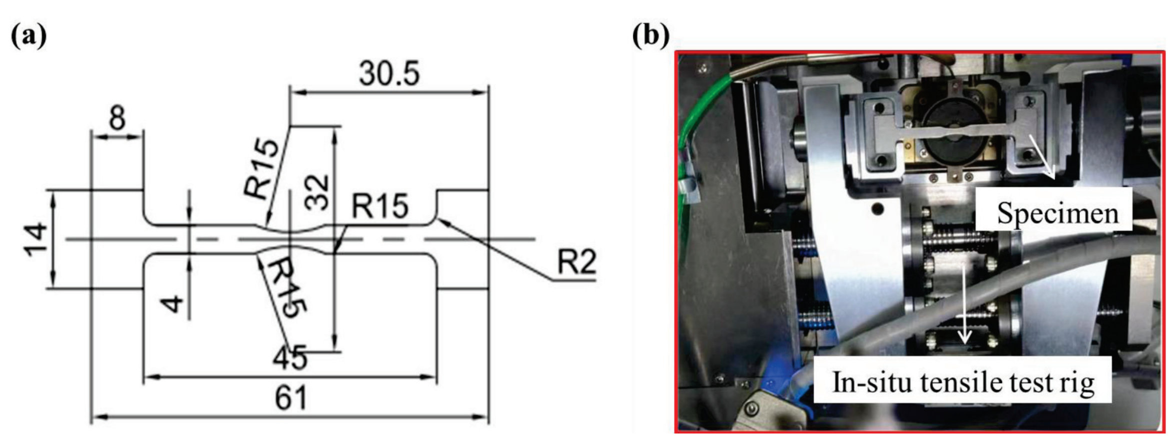


**Figure 2:** a) Dimensions of *in-situ* tensile specimens (unit: mm), b) *in-situ* tensile test rig

reduction rates were tested using an Instron 5969 electronic universal testing machine. The microhardness in the vicinity of the SiC particles was measured using a nanoindentation tester (UNHT).

## 3 RESULTS AND DISCUSSION

Rolling exerts a significant influence on the defects present in 2009Al/SiCp composite materials.[17] **Figure 3(a–b)** illustrates the presence of numerous microcracks and pores in the 2009Al matrices and at the SiC/Al interfaces in the as-sintered materials, indicating weak bonding between the SiC particles and the matrix in the sintered state.[18]

**Figure 3c–3h** displays the microstructures of the as-rolled specimens at rolling reduction rates of (30, 50 and 70) %, respectively. It can be observed that the defects, such as microcracks and pores, gradually decrease with increasing rolling reduction.[19] At the reduction rate of 70 %, the defects are nearly eliminated (**Figure 3(g–h)**). However, when the rolling reduction rate increases to 93 % and the thickness of the plate reaches approximately 0.2 mm (**Figure 3(i–j)**), long cracks appear along the rolling direction. This phenomenon can be attributed to the higher cooling rate experienced by the thin plate compared to thicker ones, leading to reduced formability of the materials.[20,21] Additionally, the rolling processes result in a refinement of the SiC particle size. **Figure 3(f)** proves that the SiC particles break during rolling.

As shown in **Figure 4(a–e)**, the average size of SiC particles in the as-rolled specimens decreases as the reduction rate increases.[22] When the reduction rate reaches 93 %, the particle size of SiC decreases to 12 μm.

**Figure 5** illustrates the SEM *in-situ* tensile results for the as-sintered and as-rolled materials. In the as-sintered specimens, cracks primarily initiate at the Al/SiC interfaces and pores during the early stage of the tensile test, indicating that defects are the main sources of these cracks.[23,24] In the later stages of the tensile test, cracks propagate along the grain boundaries within the aluminum matrices. When encountering SiC particles, the cracks propagate along the Al/SiC interfaces. Fractures of SiC particles can be observed in the as-rolled specimens, as shown in **Figure 5(j)**, providing additional

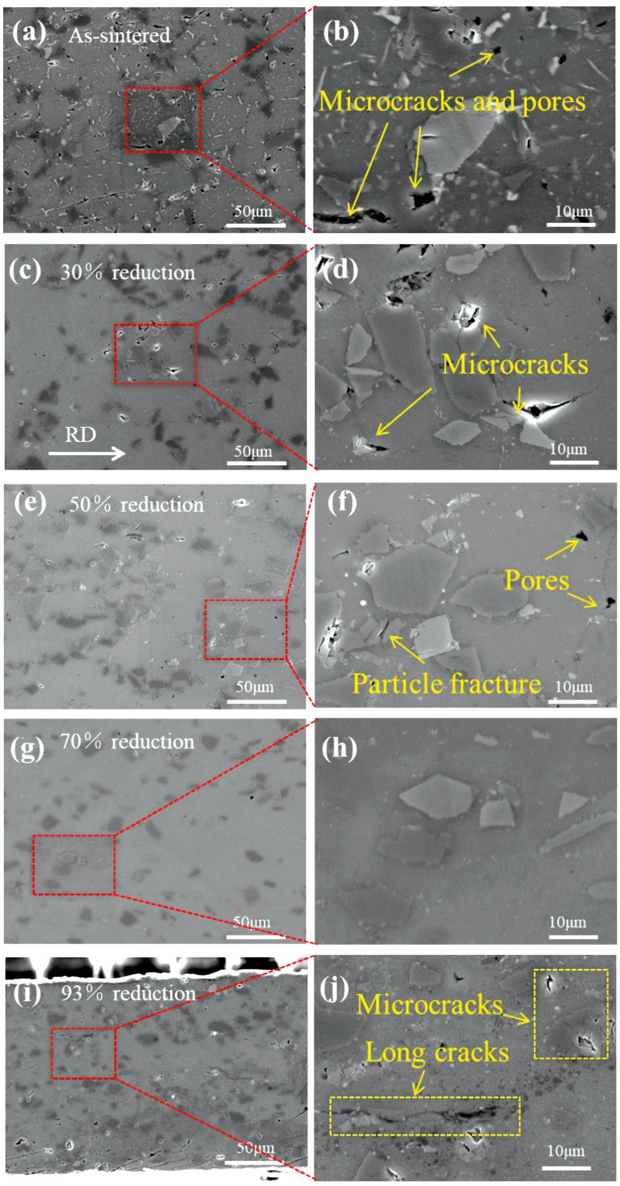


**Figure 3:** SEM micrographs of the samples: (a–b) before rolling, and after (c–d) 30 %, (e–f) 50 %, (g–h) 70 %, and (i–j) 93 % reduction

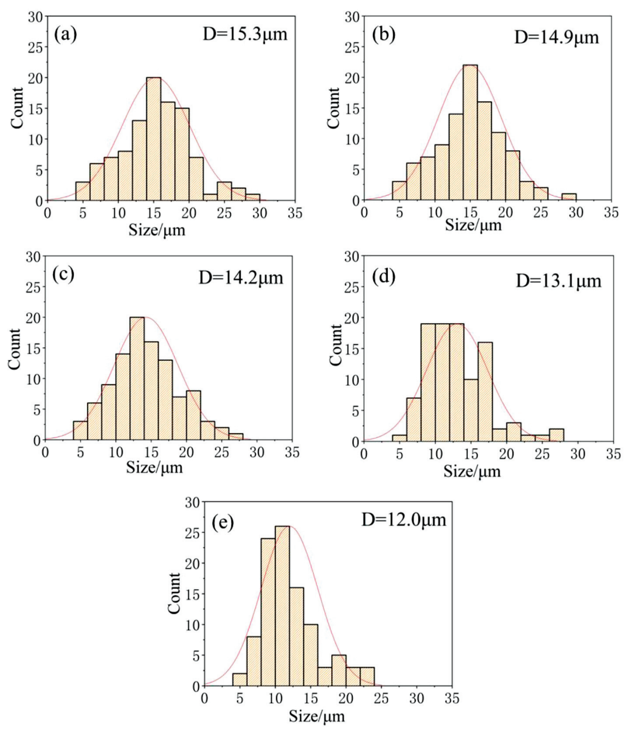


**Figure 4:** SiC particle size distribution of the samples: a) before rolling, and after b) 30 %, c) 50 %, d) 70 %, and e) 93 % reduction

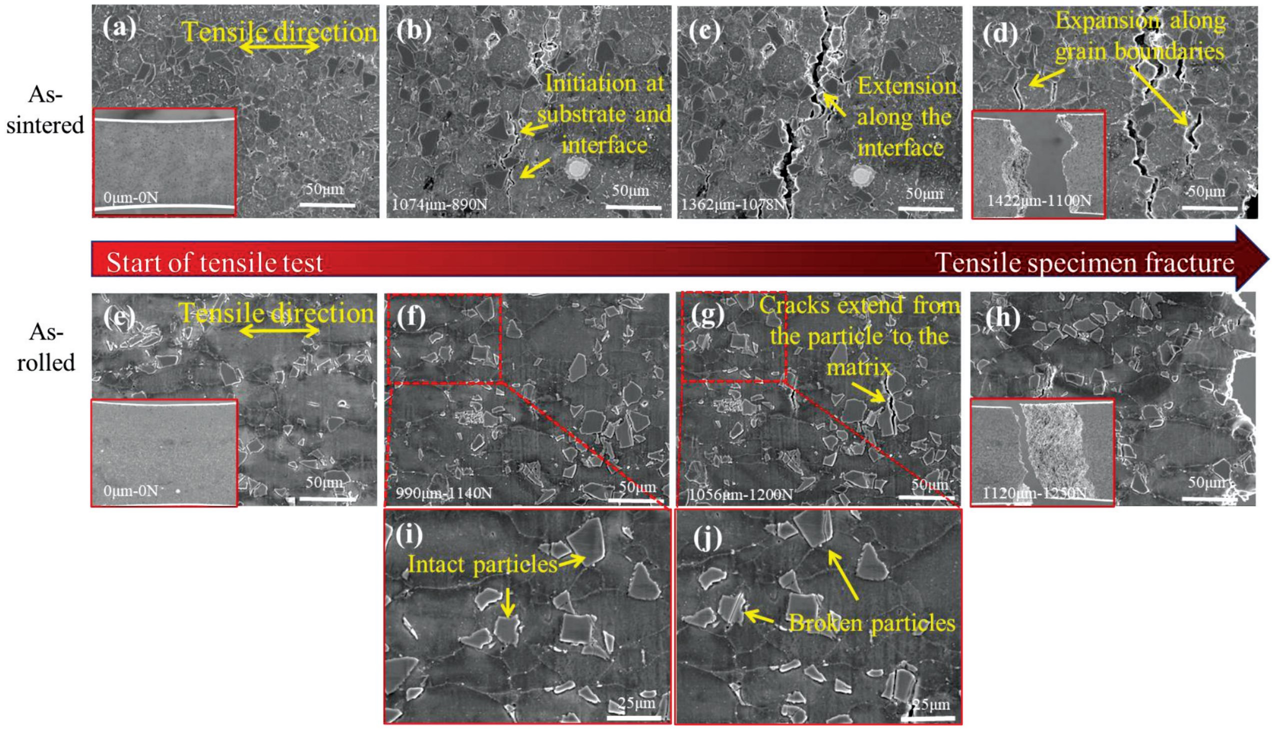


**Figure 5:** SEM *in-situ* observation of the tensile process: (a–d) as-sintered, (e–j) as-rolled specimens

sources for crack initiation and propagation towards the interface and the matrix.

Rolling has a significant impact on the microstructure and morphology of defects in the 2009Al/SiCp composites, consequently influencing their fracture behavior. The as-sintered composites exhibit a high susceptibility to fracture at the Al/SiC interfaces, indicating a relatively weak interfacial bonding strength. However, the rolling processes effectively eliminate the pores and strengthen the interfaces, thereby altering the paths along which cracks propagate during tensile tests.

The microhardness test results, as depicted in **Figure 6(a,b,c)**, indicate that the 2009Al matrices in the vicinity of SiC particles are effectively strengthened by the rolling processes. Nanoindentation was performed at four points within the 2009Al matrices, located at distances of (1, 2, 3, and 5) μm from the SiC particles. **Figure 6** shows that during the rolling processes, the presence of SiC particles hinders the movement of dislocations, leading to a significant increase in dislocation density within the material. This results in the formation of dislocation plugging areas near the interface, and within the aluminum matrix. The hardness of the dislocation plugging areas within the aluminum matrix is significantly higher than that of the surrounding aluminum matrix, thus contributing to the overall improvement in the hardness due to rolling. The SiC particles act as dislocation pinning points within the 2009Al matrices, leading to the material strengthening through dislocation strengthening and grain size reduction.[19] Moreover, plastic deformation enhances the interfacial bonding to a certain extent.[24] Con-

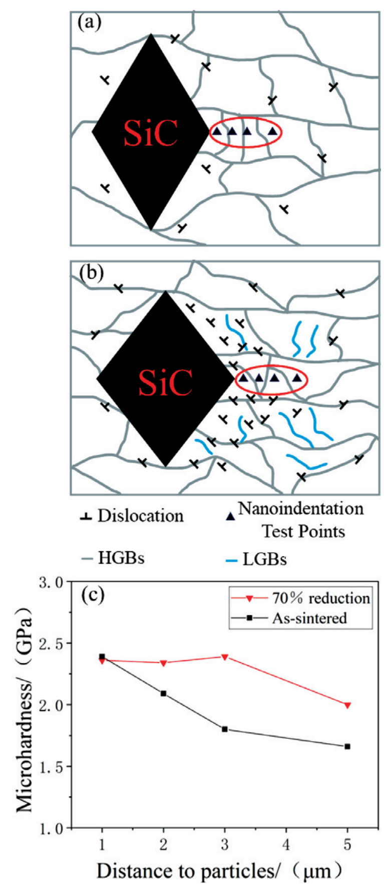


**Figure 6:** a), b) Schematic representation of the evolution and interaction of dislocations, SiC particles and grain boundaries before and after rolling; c) hardness of the interfacial microzone with distance before and after rolling

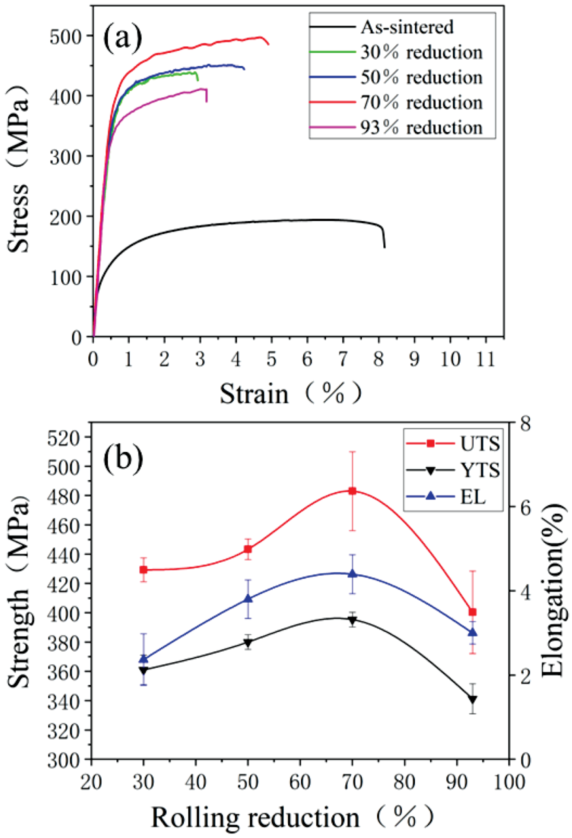


**Figure 7:** a), b) Tensile properties with different rolling reductions

sequently, the mechanical load can be effectively transferred to the SiC particles through the interface. Additionally, rolling induces internal damage to the SiC particles, rendering them more susceptible to crack initiation during tensile tests.

**Table 2:** Comparison of mechanical properties between sintered and rolled states

| | YTS (MPa) | UTS (MPa) | EL (%) |
|---|---|---|---|
| As-sintered | 103.3 ± 5.2 | 199.3 ± 6.8 | 8.2 ± 0.2 |
| As-rolled | 395.3 ± 5.0 | 483.0 ± 26.8 | 4.4 ± 0.5 |

**Figure 7(a,b)** illustrates the tensile properties under different rolling reduction rates. The yield tensile strength (YTS) and ultimate tensile strength (UTS) exhibit a significant improvement after rolling, while the elongation (EL) decreases.[25] The specific values are provided in **Table 2**.

An increase in the strength can be primarily attributed to the elimination of defects and refinement of the microstructure, facilitating an effective transfer of mechanical loads from the 2009Al matrices to the SiC particles. However, as the rolling reduction rate further increases to 93 %, both the strength and elongation of the material decrease. This reduction can be attributed to the emergence of long cracks within the material.

## 4 CONCLUSIONS

In this study, 2009Al/SiCp thin strips were fabricated using hot rolling. The influence of the reduction rate on the microstructure and fracture behavior of the composite materials was systematically investigated. The conclusions can be drawn as follows:

1) Rolling significantly enhances the mechanical strength of the 2009Al/SiCp composites. The current reduction rate of 70 % yields the highest YTS of 395.3 ± 5.0 MPa, which is significantly higher than the YTS of the as-sintered materials (103.3 ± 5.2 MPa). However, further increasing of the reduction rate to 93 % leads to the presence of long cracks in the materials, causing a decrease in both strength and elongation.

2) Increasing the reduction rate results in the refinement of SiC particles and a gradual elimination of defects within the Al matrix. Rolling expands the region strengthened by dislocations around the interface and improves the interfacial bonding strength of Al/SiC. However, the high reduction rate of 93 % introduces new microcracks, leading to edge cracking of the strips.

3) The reduction in defects within the Al matrix and the enhancement of interfacial bonding allow for a more efficient transfer of mechanical loads to the SiC particles. In the as-sintered materials, cracks primarily initiate at the Al/SiC interfaces and propagate along the grain boundaries. Conversely, in the as-rolled materials, the load-bearing effect of SiC particles is effectively pronounced.

Hence, for sintered AMC materials, applying large deformation through rolling proves to be an effective method for controlling defects and improving mechanical properties. This study provides guidance for a large-scale production of particle-reinforced AMC thin strips.


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