



Effects of reciprocating extrusion process on mechanical properties of AA 6061/SiC composites

Veysel ERTURUN¹, M. Baki KARAMIŞ²

1. Faculty of Aeronautics and Astronautics/Airframes and Powerplants, Erciyes University, Kayseri 38039, Turkey;

2. Department of Mechanical Engineering, Erciyes University, Kayseri 38039, Turkey

Received 18 March 2015; accepted 14 October 2015

Abstract: A reciprocating extrusion (RE) process was used to improve the mechanical properties of Al-based composite manufactured using cast and powder metallurgy (PM). AA 6063 cast and AA 6061 powders were used as the matrix materials, and the matrix was reinforced by 5% SiC (volume fraction) particles. The hardness and grain size of extruded samples decrease with increasing the number of extrusion pass, while the toughness and ductility increase. As the tensile strength of the samples decreases, the elongation of the extruded samples increases. Consequently, reciprocating extrusion is an effective method for improving the mechanical properties of metal matrix composites (MMC).

Key words: reciprocating extrusion; metal-matrix composites; aluminum alloy; mechanical properties

1 Introduction

There are several studies about severe plastic deformation (SPD) methods. A SPD method applied at the recrystallization temperature is the most effective method for increasing the mechanical properties of composites via grain refining. The studies [1] have been conducted worldwide to improve the mechanical properties of metal matrix composites (MMC) using different SPD methods. Aluminum matrix composites (AMCs) have attracted considerable interest from the aerospace, defense and automotive industries because of their light mass and high performance.

Several comprehensive studies have focused on improving the microstructure and mechanical properties of AMCs via reciprocating extrusion (RE). RE is one of the best SPD methods for improving the mechanical properties and eliminating the pores in the composite structures [1–3].

The effects of RE processing on the microstructural and mechanical properties of the composite were examined to aid the development of new ways to refine the nonferrous alloy. The results demonstrated that RE processing was very useful for refining the nonferrous alloy. As the number of RE pass increases, the refining

effect increases, that is, the distribution of particles in the composite becomes more uniform [4,5]. The mechanical properties of the composite could be increased by the RE process and the properties were better compared with the as-cast condition after the RE [6]. As the temperature rises, the tensile strength is reduced. Strong and ductile alloys were developed using RE processing [7]. A superior specific strength of the alloys could be achieved using RE directly from the as-cast billet. The pronounced strengthening mechanism could be linked to the high volume fraction of fine-grained matrix [8].

In another study, mixed AA 6061 and Al_2O_3 powders were hot pressed into billets. The billets were deformed by 30 passes at 460 °C through the RE process, and the Al_2O_3 particles were dispersed uniformly in the matrix. The composites exhibited excellent ductility due to the mechanical kneading process of RE [9].

2024 Al-based composites, reinforced using a hybrid of SiC whiskers and SiC nanoparticles, were fabricated using a squeeze casting route. The experimental results showed that the SiC nanoparticles were more effective in improving the hardness and tensile strength of the composites than the SiC whiskers [10].

To produce Al–20%Si (mass fraction) alloys with fine and uniform microstructures that have superior

properties, rapidly solidified layers and cast billets were used as the starting materials in a RE process. The results showed that the interfaces between the layers of the rapidly solidified alloys could be fully eliminated, and the strength and ductility were both improved as the number of RE pass increased [11,8].

Equal-channel angular extrusion/processing (ECAE/ECAP) is one type of SPD. The research on ECAE processing presented an overview of the ultra fine AA 6061 materials. The best process route for ultrafined processing of bulk material was identified. Through experiment, the best grain refinement was only at ultrafined level and the finest grain size was 0.71 μm . In addition, the relationship between the mechanical properties and the number of pass was compared [12]. As an alternative method, ECAP using accommodated back pressure was used to reinforce the fine atomized Al powder in an another study. The effect of ECAP on the consolidation behavior of powders, and the microstructures and mechanical properties of resulted compacts was presented in comparison with that of the conventional direct extrusion (DE) process [13].

A new method of SPD for producing bulk fine-grained materials was proposed and called the cross-channel extrusion (CCE) process [14]. The effects of the CCE process on the microstructure and mechanical properties of AA 6061 alloy were also investigated. After 8 extrusion passes at temperatures ranging from 200 to 300 $^{\circ}\text{C}$, a fine-grained structure was observed with a grain size of 0.2–4 μm . Increased hardnesses and tensile strengths were obtained from the samples extruded at lower temperatures. Moreover, the dispersion was gradually refined with increasing the extrusion pass and resulted in increased elongation [15]. The relationship between the microstructures and the mechanical properties of the CCE processed AA 6061 alloy caused by different heat treatments was investigated. The results indicated that the post-CCE was a suitable method for producing Al alloy with improved strength [16].

The microstructures and mechanical properties of the hot extruded Mg alloy were investigated. The results showed that the use of a rapidly solidified powder could lead to effective grain refinement, which in turn resulted in an improved mechanical response, especially compared with that of the conventionally extruded cast materials. The ultimate strength, yield strength and elongation were also obviously improved [17,18].

The aim of this study is to evaluate the microstructures and mechanical properties of the reciprocatingly extruded AA 6063 cast and AA 6061 powder alloys reinforced by SiC particles, and to obtain the refined grains in Al matrix composites by the application of a new severe deformation method. The effects of the process parameters on the grain refining and mechanical properties of the processed composites material were investigated.

2 Experimental

2.1 Materials and MMC preparation

AA 6063 and AA 6061 were selected for the extrusion billets. The 6063 Al alloy was melted in a graphite crucible and 5% SiC (volume fraction) particles with size of 20 μm were added to the melted material by stirring. Thus, the cast billets, either with or without SiC, were obtained as extrusion billets. Additionally, 6061 Al powder particles (72 μm in size) were mixed with 5% SiC particles with 20 μm in size (volume fraction) for 1 h using a shaker-mixer. The mixed composite powders were cold packed at a pressure of 20 MPa as extrusion billets. These billets were then sintered at 600 $^{\circ}\text{C}$ and a pressure of 10 MPa under an argon atmosphere. All the extrusion billets that were prepared using powder metallurgy (PM) and stir-cast methods have dimensions of 29.5 mm in diameter and 42 mm in height (Fig. 1). The compositions of the materials are listed in Table 1.

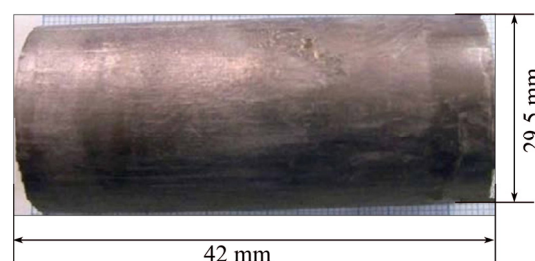


Fig. 1 Illustration of billet produced using PM

2.2 Extrusion process

Both the composites and the unreinforced billets were reciprocatingly extruded using an extrusion press machine that was specially designed. The RE process is shown schematically in Fig. 2. The process has a symmetrical design comprising two containers: a die and two punches. These parts were made of H13 steel with a

Table 1 Chemical compositions of materials (mass fraction, %)

Sample	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn	Others
AA 6061	95.8–98.6	0.040–0.35	0.15–0.40	≤0.70	0.80–1.20	≤0.15	0.40–0.80	≤0.15	≤0.25	≤0.15
AA 6063	98.5659	0.0069	0.0282	0.2576	0.5378	0.0173	0.5159	0	0.0299	0.0405

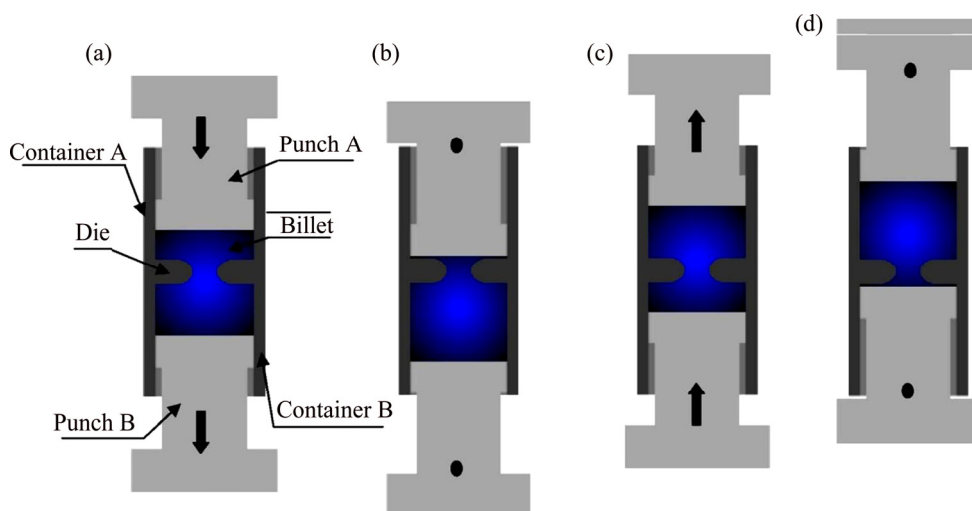


Fig. 2 Schematic illustration of reciprocating extrusion: (a) Start of step 1; (b) End of step 1; (c) Start of step 2; (d) End of step 2

hardness of HRC 50 because they were affected by the high temperature and pressure. First, a billet is placed into Container A and then extruded into Container B using Punch A. Simultaneously, a back pressure lower than the pressure of Punch A is applied by Punch B to compress the extruded material. Thus, the material fills Container B and recovers its billet shape (1 pass). When Punch A almost reaches the die, the pressure on Punch A reduces, and the pressure on Punch B increases to perform the reverse extrusion. In this case, Punch A is slowly moved backward, and Punch B compresses the material into Container A (2 passes). The billets are repeatedly extruded upwards and downwards until the required number of pass is reached. However, for the final extrusion, Punch B is removed to yield an extruded rod with 10 mm in diameter. The meaning of 0 pass is that the billets were inserted into the container and then extruded into a rod with a diameter of 10 mm.

In this study, the billets were extruded under 17.5 MPa for 0, 1, 5, 9 and 15 passes at 400 °C, for 0, 1, 5, 9 and 13 passes at 300 °C, and for 0, 1, 2, 3, 4 and 5 passes at 200 °C. The extrusion ratios were 10:1 at 400 and 300 °C and 4:1 at 200 °C.

2.3 Microstructural analyses

The morphologies of both SiC and 6061 Al alloy powders were investigated using optical microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The samples for the metallographic examinations were polished and etched using standard procedures. The average grain size of the extruded rods was measured using the Image-Pro Plus program.

The TEM studies were performed on Al alloy samples to reveal the effect of RE passes on the grain size of composite. The samples were cut using a Struers

Minitom low-speed diamond saw. Thin foils were prepared by punching as 3-mm discs and ground to thicknesses of ~150 μm. Next, perforation was performed by electro polishing with an electrolyte solution of 20% nitric acid and 80% methanol at approximately 25 °C and 15 V in a Struers-Tenupol-5 double jet electro polisher. The samples were investigated using a JEOL 2100 transmission electron microscope (LaB₆ filament) operated at 200 kV and equipped with an Oxford EDS system. Images were taken digitally using a Gatan Model 694 Slow Scan CCD camera. A JEOL side entry single tilt goniometry was used. Bright field (BF) and selected area electron diffraction (SAED) techniques were used to investigate the microstructure. For the digital images, Gatan Digital Micrograph software was used.

The Superficial Rockwell hardness values of the samples were measured by Superficial Rockwell N scale under 15 N loads using Rockwell hardness tester with a diamond indenter, which has an advanced LCD touch screen, automatic measurement procedure, load/dwell/unload and connects with a PC or SPC network via a built-in bi-directional USB2 connector.

2.4 Tensile tests

Tensile tests were performed on the samples extruded at 400, 300 and 200 °C. After the completion of the planned number of RE pass, the samples were extruded into rods with circular cross sections for tensile testing. The tensile samples were obtained with processing dimensions (8 mm in diameter), as shown in Fig. 3.

2.5 Charpy impact tests

The samples were extruded at 200 and 300 °C and the specimens with dimensions of 55 mm × 10 mm ×

10 mm were cut from the extruded materials. Charpy impact tests were performed on these machined samples that had v-notch cut across one of the faces at the middle of a long-axis (e.g., at 50 mm).

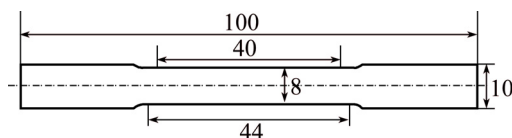


Fig. 3 Dimensions of tensile test samples (unit: mm)

3 Results and discussion

3.1 Microstructure of extruded samples

Figure 4 shows the microstructures of the samples and billets produced using the PM method and reinforced with 5% SiC. While the matrix powder and SiC particles can be observed in the microstructure of billet produced using PM, the grain boundaries in the extruded samples by 1, 5 and 9 passes cannot be observed, except for the SiC particles (Fig. 4).

As shown in Fig. 4, after the sintering of the powders, no porosity exists in the SiC particles, and the SiC particles are homogeneously dispersed within the matrix. The distribution of SiC particles is very uniform [11]. It is also noted that AA 6061–0.3 μm Al_2O_3 composites can be consolidated and fully densified from powder compact by reciprocating extrusion [9].

The grain boundaries and SiC particles can be easily observed in the image of billet (Fig. 4(a)). However, the grain boundaries of the extruded samples cannot be observed (Figs. 4(b)–(d)). For this reason, the change in

the average grain size cannot be determined in these samples after the RE process by SEM. However, the changes in grain size values can be observed by TEM [12].

The TEM images of the unreinforced and SiC-reinforced AA6061 billet (PM) and samples extruded using 1, 5, 9 or 13 passes at 300 °C were obtained (Figs. 5 and 6). The grain sizes of each image were measured using Image-Pro Plus image processing software, and the average values of grain sizes were calculated. As can be seen in the TEM images, the average grain sizes of the unreinforced samples after 1, 5, 9 and 13 passes of extrusion were determined to be 1.069, 1.273, 1.333 and 1.6 μm , respectively (Fig. 5). The hardness values of the same samples were determined to be approximately HR₁₅ 49, HR₁₅ 41, HR₁₅ 39 and HR₁₅ 33, respectively. According to this result, coarsened grain sizes and decreased hardness were realized using the same process parameters (i.e., at the processing temperature of 300 °C and extrusion ratio of 10:1) by increasing the number of pass. Therefore, the reason for the decreased hardness is the grain coarsening. Thus, the effect of severe plastic deformation on the average grain size is less than that of processing temperature of 300 °C. Considering the duration of the reversible extrusion processing, the length of the processing time increases with increasing the number of pass, therefore, the duration of the exposure at 300 °C also increases. For this reason, the average grain size increases with increasing the annealing temperature and time. It is well known that the hardness also decreases with increasing the grain size. Therefore, the observed results are as expected from the scientific point of view.

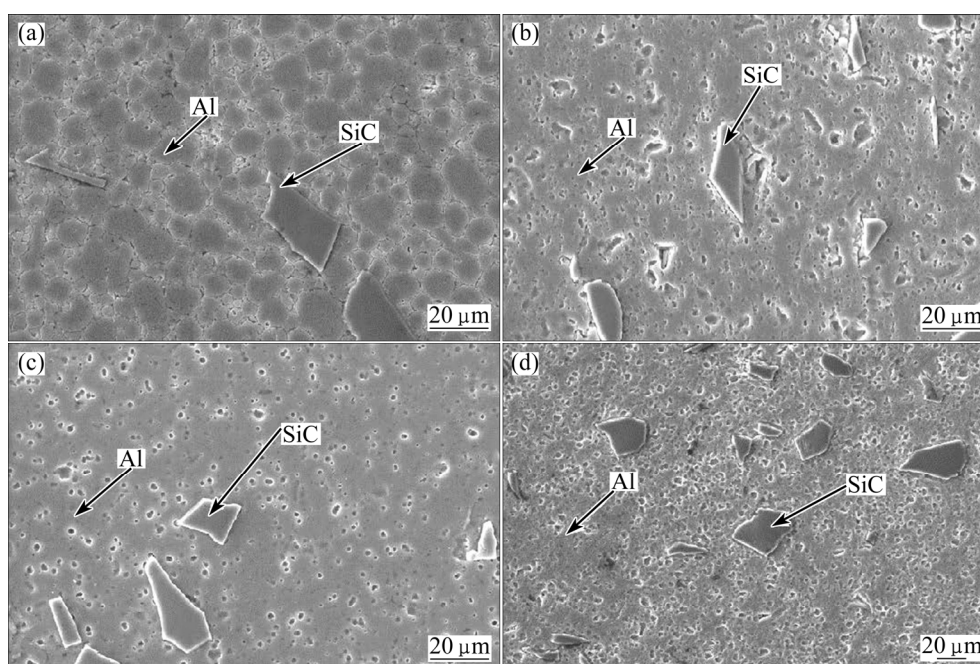


Fig. 4 Microstructures of SiC-reinforced AA 6061 samples extruded at 300 °C: (a) Billet; (b) 1 pass; (c) 5 passes; (d) 9 passes

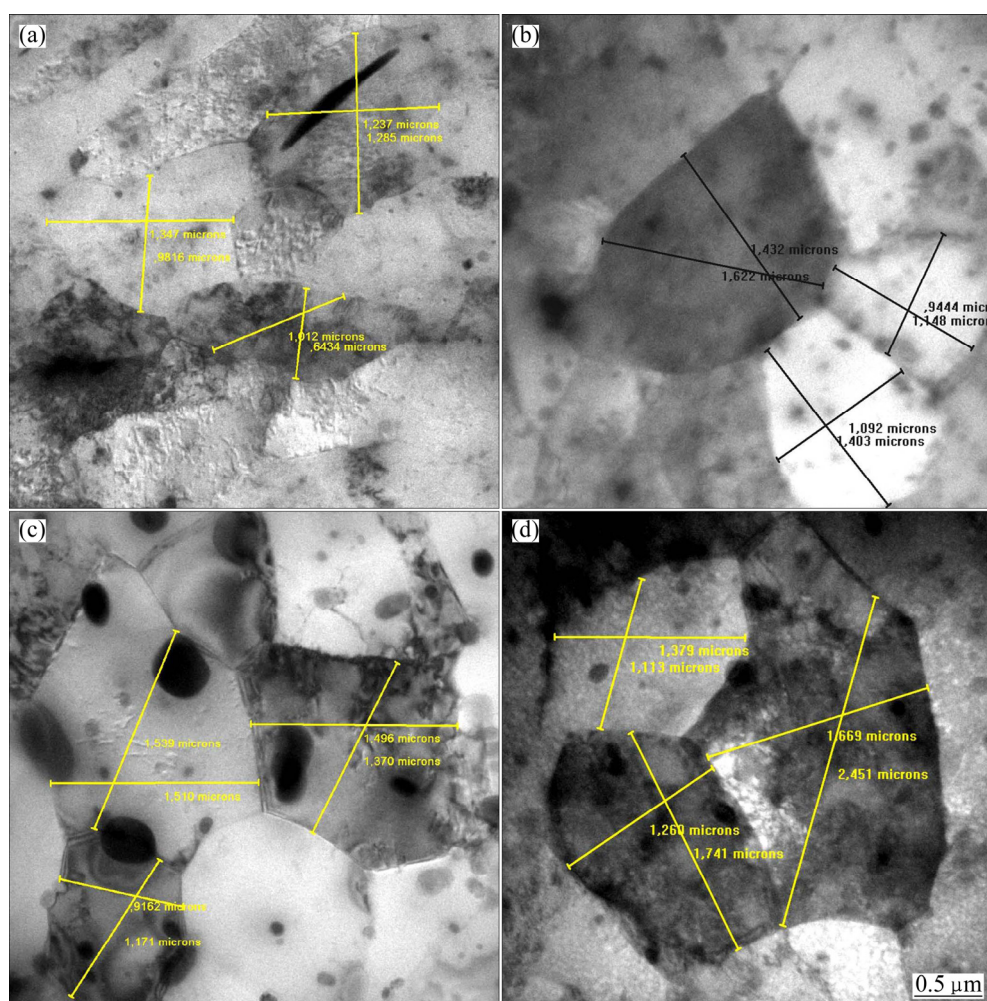


Fig. 5 TEM images of unreinforced AA 6061 samples (PM) extruded at 300 °C: (a) 1 pass (1.069 μm); (b) 5 passes (1.273 μm); (c) 9 passes (1.333 μm); (d) 13 passes (1.6 μm)

Recrystallization happened during the treatment that led to the increase of grain size and the annihilation of working hardening effect. Therefore, the extrusion treatment was carried out to form a ultra fine grain material with the formation of precipitates [16].

The TEM images of 5% SiC-reinforced samples are shown in Fig. 6. The average grain sizes of the reinforced samples extruded under the same conditions increase initially similar to the unreinforced counterparts and then decrease slightly. Because of this difference (due to a reduction in the transmission of heat by the ceramic particles in the composite), there is no an extreme difference in the Al grains during the process. However, coarsened grains are observed after 1 pass.

After the TEM analysis of samples extruded at 300 °C, the following results are obtained. Despite the exposure to severe plastic deformation, no sample shows a very high dislocation density. This observation demonstrates that the samples were subjected to heat treatment at high temperature during the deformation. The differences between the samples were ultimately

eliminated at high temperature. It is observed that the processing temperature plays an important role in the dislocation density of all samples.

The TEM images of the 1-pass unreinforced AA 6061 samples are shown in Fig. 7. There are two different sizes of precipitate in these samples. These sizes are the first group of large particles and the second group of small particles, which are higher in numbers. The small and large precipitates are marked in the circle in the TEM images. It can be seen that the dislocation density is low in the samples.

The TEM images of 5-pass samples reinforced with 5% SiC are shown in Fig. 8. There are also precipitated particles with two different sizes. These are a group of large particles and a group of small particles, which are higher in numbers. The same result was found in the images of 13-pass samples (reinforced with 5% SiC). The small and large precipitates are marked in the circle in the TEM images. There is a very low dislocation density. The 13-pass samples reinforced with 5% SiC also have precipitated particles with two different sizes,

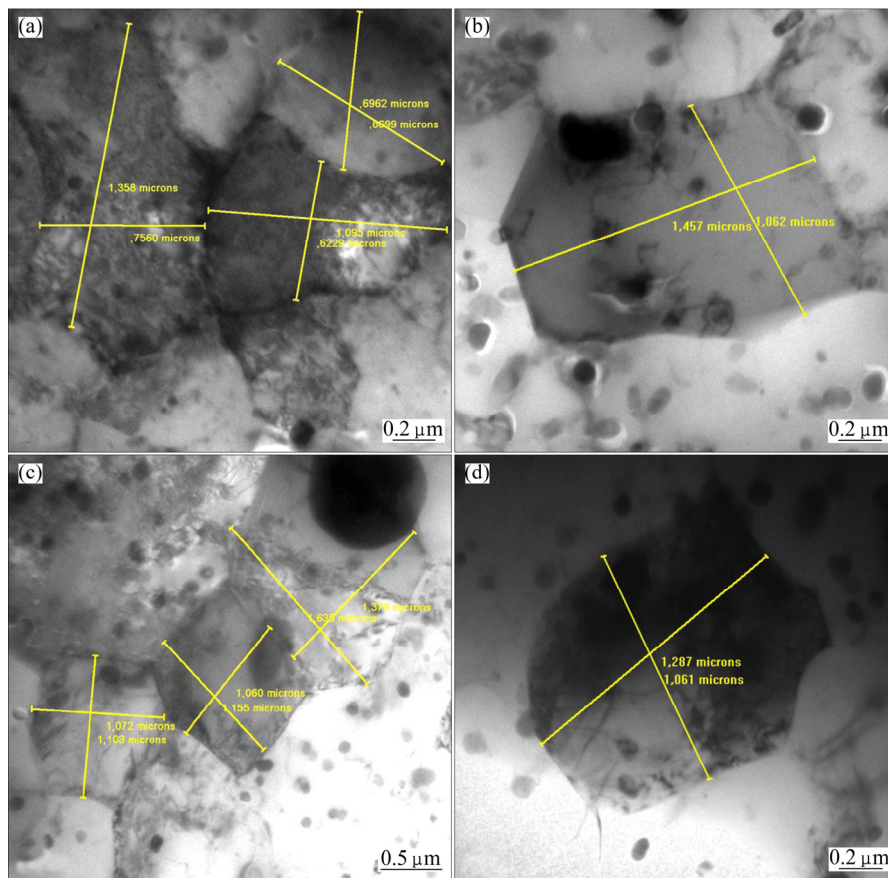


Fig. 6 TEM images of SiC-reinforced AA 6061 samples (PM) extruded at 300 °C: (a) 1 pass (0.8996 μm); (b) 5 passes (1.3222 μm); (c) 9 passes (1.234 μm); (d) 13 passes (1.014 μm)

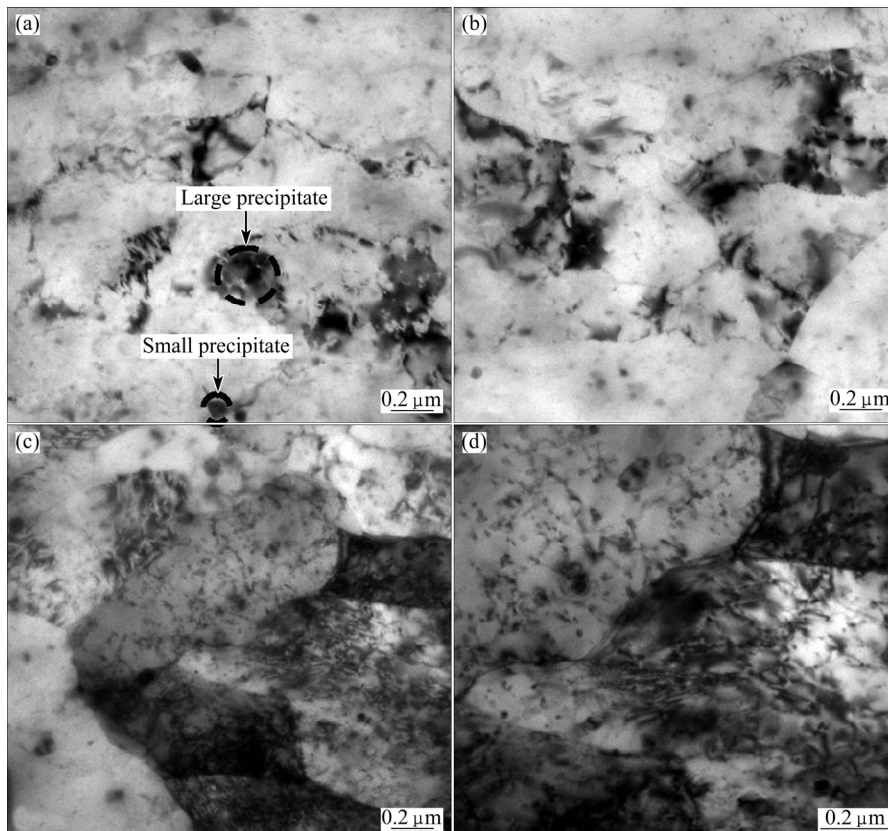


Fig. 7 TEM images of 1-pass unreinforced AA 6061 samples in various places

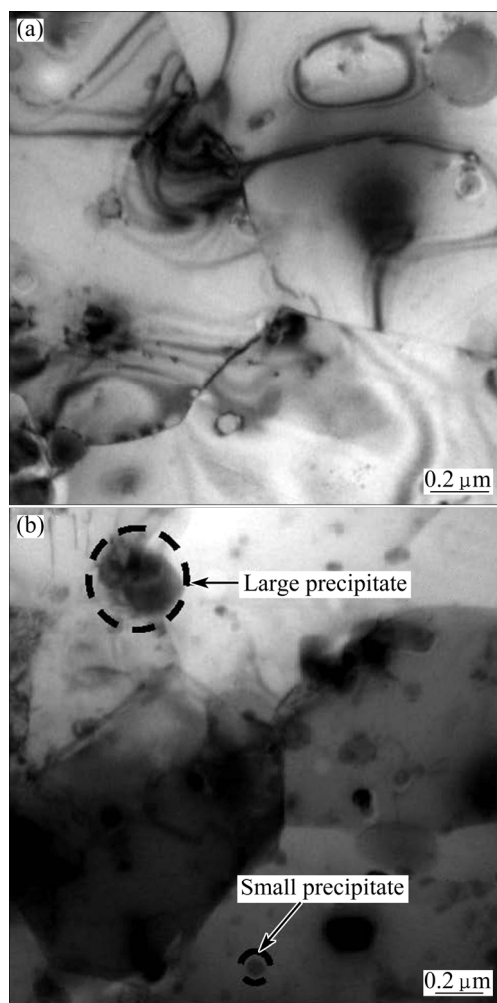


Fig. 8 TEM images of 5-pass sample reinforced with 5% SiC

but the dislocation densities of these sample are high compared with those of 5-pass samples. DU et al [19] also observed a small number of precipitates in the recrystallized grains and grain boundaries and a large number of dispersed precipitates in the unrecrystallized regions during extrusion.

The average grain sizes of the samples extruded at 300 and 200 °C are shown in Fig. 9. As the number of pass increases, the average grain size increases at 300 °C, while it decreases at 200 °C. When the temperature of the RE decreases from 300 to 200 °C, the average grain size value decreases from 1.3 to 0.4 μm, so the average grain size decreases by 59%. As a result, it is understood that the RE process temperature plays an important role in the average grain size of the samples.

The highest hardness did not coincide with the minimum average grain size (Fig. 9), the hardness was the highest after 2 passes. From the TEM results, the 2-pass samples contain precipitated particles with very small sizes, but the 3-pass samples do not contain them. The dislocation densities are also high in both samples. For these reasons, the dislocation densities of the

samples do not affect the hardening factor. It is the precipitated particles affecting the hardness of samples and not the density of dislocations. In addition, as mentioned in Ref. [20], increasing the number of extrusion pass leads to more boundaries with more superfluous dislocations.

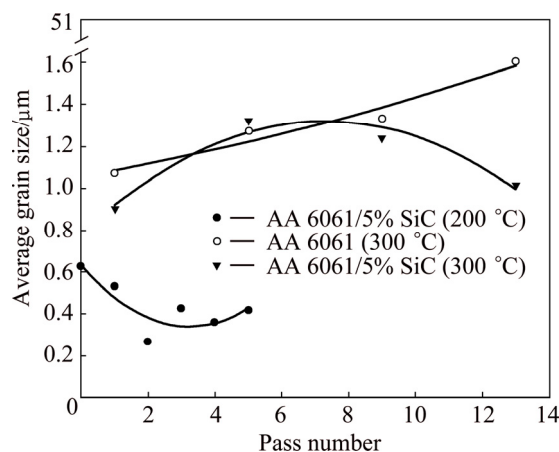


Fig. 9 Effect of multi-pass RE on average grain size of AA 6061 extruded at 300 and 200 °C

The variations in the hardness values for all samples (as-cast and powder metallurgy) extruded at 400, 300 and 200 °C are shown as a function of the number of pass (Fig. 10). As the number of pass increases, the hardness initially increases and then decreases for the cast samples (Fig. 10(a)). Despite this observation, the hardness values of the samples increase with increasing the number of pass at 200 °C. However, the hardness values of the reinforced and unreinforced samples remain constant at 400 °C and change slightly at 300 °C. It is understood that the extrusion temperature plays an important role in the hardness values. The hardness increases within 2 passes and then decreases with the subsequent passes. Here, the effect of temperature dominates the combined effects of the temperature and deformation degree.

The changing hardness of the PM samples with increasing the number of pass is shown in Fig. 10(b). A reduction in the hardness is clearly observed with increasing the process temperature. At 400 °C which is above the recrystallization temperature of Al, the hardness values do not change. It is observed that the hardness of the RE sample processed at 200 °C is higher than that of the RE sample processed at 300 °C. The hardness initially increases and then decreases at both temperatures. This behavior does not reduce the hardness of billets at 200 °C. The hardness values of the 9- and 13-pass samples are less than that of the billets processed at 300 °C.

The hardness value of the 5-pass PM samples reinforced with SiC and extruded at 300 °C is lower than

that of the 5-pass PM samples extruded at 200 °C. The hardness value of the 5-pass PM samples extruded at 300 °C does not increase at all, approximately equals that of the billets, as shown in Fig. 10(b).

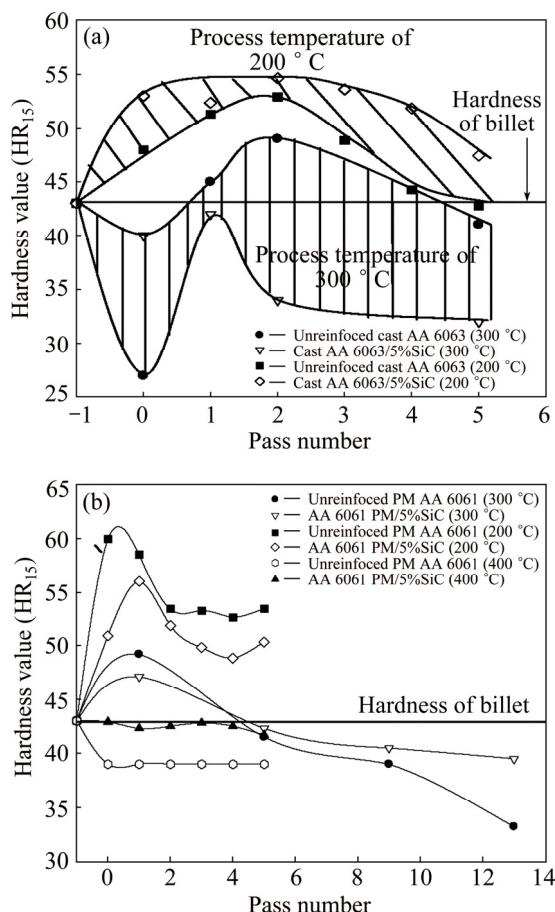


Fig. 10 Effect of multi-pass RE on hardness values of as-cast samples (a), and powder metallurgy samples (b) extruded at 400, 300 and 200 °C

All samples processed at the recrystallization temperature (200 °C) experience a little hardening and give higher hardness values than the billets (Fig. 10). However, the hardness tends to decrease with increasing the number of pass. The cast samples extruded at 200 °C show a similar trend of hardness (Fig. 10(a)). In general, the hardness values initially increase and then decrease with increasing the number of pass. With an increasing number of RE pass, the hardness values of powder metallurgy samples drastically increase after 1 pass of extrusion at 200 and 300 °C, caused by the work hardening and fine-grained strengthening effects, as shown in Fig. 10(b). The process temperature does not affect the change in the hardness with increasing the number of pass, which is the most influential factor in terms of the hardness values. These results parallel a previous study from Ref. [15].

The average grain sizes and hardness values as a function of the number of RE pass are shown in Fig. 11.

As the number of pass increases from 1 to 5, the average grain size increases by approximately 20%, and the hardness decreases by 15.5%. When the number of pass increases from 5 to 9, the average grain size increases by 4.7%, and the hardness decreases by 6%. As the number of pass increases, the rate of reduction of the hardness remains close to that of increase of the average grain size. The average grain size was expected to decrease as the number of pass increases. In contrast, it is found to increase. The extrusion temperature plays an important role in the average grain size of the reciprocating extruded and unreinforced samples.

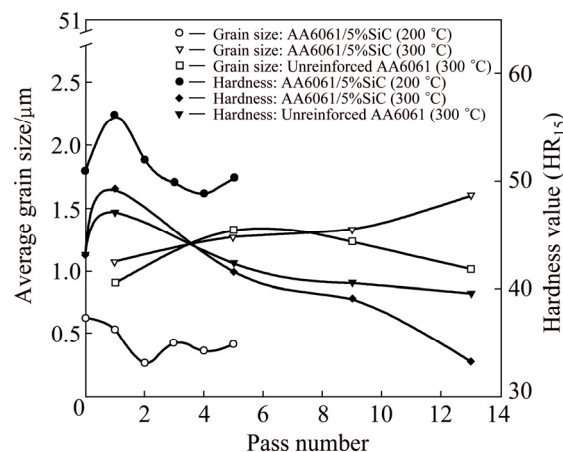


Fig. 11 Effect of multi-pass RE on average grain sizes and hardness values of AA 6061 sample extruded at 300 and 200 °C

3.2 Mechanical properties of extruded samples

As shown in Fig. 12, the absorbed energy values of the tensile samples generally increase with increasing the number of pass at 300 and 200 °C. The increase of absorbed energy values after RE is related to the microstructure of the composite and the microstructural changes during RE. These microstructural characteristics were mostly eliminated during multi-pass RE. The grain refinement occurred, and then, the composite became

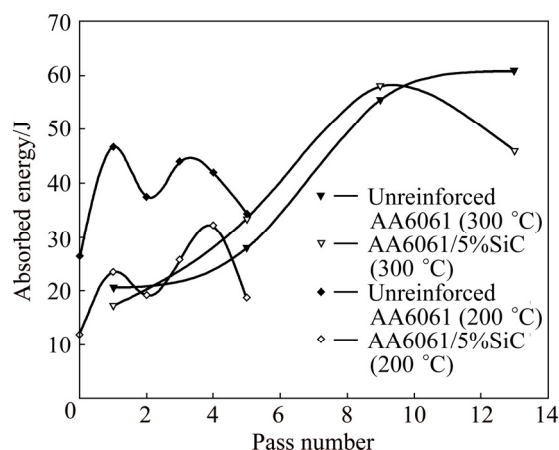


Fig. 12 Effect of multi-pass RE on absorbed energy values of AA 6061 PM samples extruded at 300 and 200 °C

more uniform, which reduced the incompatibility between the phases and improved the ductility and absorbed energy values. The observed energy at 200 °C is higher than that at other temperatures (Fig. 12).

The energy absorption characteristics of samples are similar at 300 and 200 °C. That is, the reinforced and unreinforced samples demonstrate increased tensile energy absorption for up to 9 passes, and the energy absorption of the reinforced samples decreases in the 13th pass at 300 °C.

The ultimate tensile stress (UTS) values for all PM samples as a function of the number of pass are shown in Fig. 13. A comparative evaluation of the ultimate tensile stress values as a function of process temperature shows that the salient point is that the ultimate tensile stress of the samples extruded at 200 °C is much higher than that of the samples extruded at 300 °C. The ultimate tensile stress of the samples extruded at 300 °C generally decreases, similarly, the ultimate tensile stress of samples extruded at 200 °C generally decreases after 1 pass. The ultimate tensile stress values of the samples extruded at 200 °C demonstrate a nonmonotonic change with increasing the number of pass, first increasing and then decreasing. However, the unreinforced samples extruded at 200 °C reverse at the highest values, and the reinforced samples extruded at 300 °C change at the minimum values. Another noteworthy point is that the ultimate tensile stress of the reinforced samples extruded at 200 °C after 1 pass is much higher than that of the unreinforced samples after 2–5 passes. This sample has the finest grain size of 0.26 μm . In another researches, the best grain refinement was only at ultrafine level and the finest grain size was 0.71 μm [12], the grain size of the extruded sample was 0.2–0.5 μm [16] and a fine-grained A356 bulk alloy with a subgrain size of 0.5–3 μm was successfully produced by cross-channel extrusion process [14].

As mentioned before, the hardness value increases after 1 pass of extrusion, then starts to decrease after the

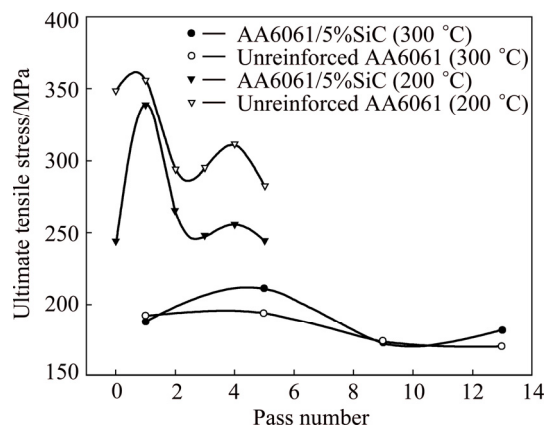


Fig. 13 Effect of multi-pass RE on ultimate tensile stress values of AA 6061 PM samples extruded at 300 and 200 °C

2nd pass, and continues to decrease. This tendency is exactly the same as that of the measured ultimate tensile values. It is also noted that the variation trend of UTS with the number of ECAE pass is almost the same as the hardness change [12]. The major reasons for the softening effect are the deformation induced homogenization of the composite and the reduction in the volume fraction of the hard phase due to dissolution and breakage [20].

The hardness and tensile strengths of the alloy increase after 1 pass of RE and then decrease gradually as the number of RE pass increases. The softening effect of the RE processing is due to the decreased amount of deformation. The relatively high processing temperature is effective in decreasing the amount of deformation during the RE process.

The rupture strain values of samples extruded at 300 °C change for up to 9 passes and for up to 4 passes in the samples extruded at 200 °C [4]. The unreinforced samples also show the same behavior (Fig. 14). The reinforced and unreinforced samples extruded at 200 °C generally experience elongation for up to 4 passes. After 4 passes, they experience a decreased elongation. During the 9th to the 13th passes of the reinforced and unreinforced samples extruded at 300 °C, the elongation is higher than that of other samples. The elongation of the 13-pass sample is approximately 5 times that of the 1-pass sample. The total elongation to failure of the alloy increases dramatically with increasing the number of extrusion pass [19,20].

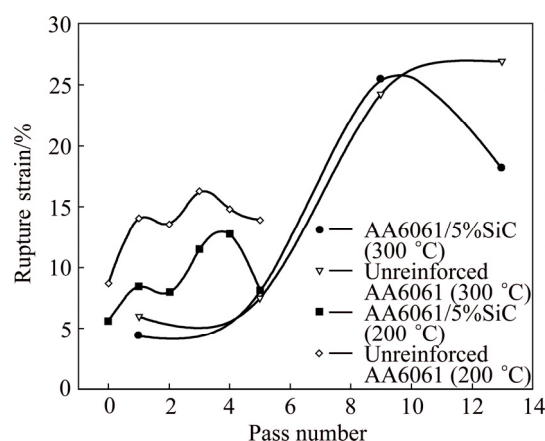


Fig. 14 Effect of multi-pass RE on rupture strain values of AA 6061 PM samples extruded at 300 and 200 °C

As the extrusion temperature increases, the hardness value decreases due to the structural coarsening and grain growth. The RE process also increases the ductility of the composites, as shown in Fig. 14. The composite shows very limited ductility up to 5 passes. The total elongation to failure, as a measure of ductility, of the alloy increases dramatically from the 9th to the 13th

passes [11]. The decrease of ductility after extrusion processing was observed in many extrusion processed Al alloys [12]. The heat treated sample expectably showed the highest strength, however, the elongation was lowered [16].

The cause of this behavior is the average grain size rather than the hardness. The average grain sizes of the 9- and 13-pass samples at 300 °C are shown in Fig. 11. The composite matrices contain high porosities and large voids. These microstructural features are mostly eliminated during the multi-pass RE and the grain refinement occurs. Then, the composites become more uniform, which reduces the incompatibility between the phases. Thus, the ductility of the samples is improved. Many researchers [13,19,21] reported that the strength and ductility can be improved by altering the grain size using an extrusion. The more the extrusion passes, the better the mechanical properties [11]. The composites exhibit excellent ductility, probably due to the full density and the uniform dispersion of particles caused by mechanical kneading of RE [9].

4 Conclusions

1) Fine-grained Al matrix composites were produced using a RE process.

2) The hardness value decreases with increasing the extrusion temperature due to the structural coarsening and grain growth. The RE processing temperature plays an important role in the average grain size and hardness value of the samples.

3) The ultimate tensile stress of samples processed at 300 °C decreases as the number of pass increases, while the tensile strength decreases and the rupture strain increases.

4) The composites exhibit excellent ductility due to the mechanical kneading in the reciprocating extrusion process.

Acknowledgements

The authors would like to thank the Scientific and Technological Research Council of Turkey (TUBİTAK) and Erciyes University for their financial support of the present study under project Nos. 108M562 and FBD-09668, respectively.

References

- [1] LIN J B, WANG Q D, CHEN Y J, LIU M P, ROVEN H J. Microstructure and texture characteristics of ZK60 Mg alloy processed by cyclic extrusion and compression [J]. Transactions of Nonferrous Metals Society of China, 2010, 20(11): 2081–2085.
- [2] KARAMIS M B, SARI F N, ERTURUN V. Friction and wear behaviors of reciprocatingly extruded Al–SiC composite [J]. Journal of Materials Processing Technology, 2012, 212: 2578–2585.
- [3] KARAMIS M B, ERTURUN V, SARI F N. Investigation on effects of reciprocating extrusion process on microstructure of AA 6061 based composites [J]. Materials Science and Technology, 2012, 28: 1379–1384.
- [4] ZHANG Z M, XU C J, GUO X F, JIA S Z. Reciprocating extrusion of in situ Mg₂Si reinforced Mg–Al based composite [J]. Acta Materialia, 2008, 21: 169–177.
- [5] LEE S W, WANG H Y, CHEN Y L, YEH J W, YANG C F. An Mg–Al–Zn alloy with very high specific strength and superior high-strain-rate superplasticity processed by reciprocating extrusion [J]. Advanced Engineering Materials, 2004, 6: 1438–1656.
- [6] GUO X F, REMENNIK S, XU C J, SHECHTMAN D. Development of Mg–6.0%Zn–1.0%Y–0.6%Ce–0.6%Zr magnesium alloy and its microstructural evolution during processing [J]. Materials Science and Engineering A, 2008, 473: 266–273.
- [7] GUO X F, SHECHTMAN D. Reciprocating extrusion of rapidly solidified Mg–6Zn–1Y–0.6Ce–0.6Zr alloy [J]. Journal of Materials Processing Technology, 2007, 187–188: 640–644.
- [8] LEE S W, CHEN Y L, WANG H Y, YANG C F, YEH J W. On mechanical properties and superplasticity of Mg–15Al–1Zn alloys processed by reciprocating extrusion [J]. Materials Science and Engineering A, 2007, 464: 76–84.
- [9] CHU H S, LIU K S, YEH J W. Aging behavior and tensile properties of 6061Al–0.3 μm Al₂O_{3p} particle composites produced by reciprocating extrusion [J]. Scripta Materialia, 2001, 45: 541–546.
- [10] GENG Lin, ZHANG Xue-nan, WANG Gui-song, ZHENG Zhen-zhu, XU Bin. Effect of aging treatment on mechanical properties of (SiC_w+SiC_p)/2024Al hybrid nanocomposites [J]. Transactions of Nonferrous Metals Society of China, 2006, 16(2): 387–391.
- [11] YEH J W, YUAN S Y, PENG C H. A reciprocating extrusion process for producing hypereutectic Al–20wt.% Si wrought alloys [J]. Materials Science and Engineering A, 1998, 252: 212–221.
- [12] FU M W, THAM Y W, HNG H H, LIM K B. The grain refinement of Al-6061 via ECAE processing: Deformation behavior, microstructure and property [J]. Materials Science and Engineering A, 2009, 526: 84–92.
- [13] MARTIN B, FRANTISEK S, OTTO B, REQUENA G. ECAP vs. direct extrusion—Techniques for consolidation of ultra-fine Al particles [J]. Materials Science and Engineering A, 2009, 504: 1–7.
- [14] CHOU C Y, LEE S L, LIN J C. Effects and deformation characteristics of cross-channel extrusion process on pure Sn and Al–7Si–0.3Mg alloy [J]. Materials Chemistry and Physics, 2008, 107: 193–199.
- [15] CHOU C Y, LEE S L, LIN J C. Effects of cross-channel extrusion on microstructure and mechanical properties of AA6061 aluminum alloy [J]. Materials Science and Engineering A, 2008, 485: 461–467.
- [16] CHOU C Y, HSU C W, LEE S L. Effects of heat treatments on AA6061 aluminum alloy deformed by cross-channel extrusion [J]. Journal of Materials Processing Technology, 2008, 202: 1–6.
- [17] ELSAYED A, KONDOH K, IMAI H, UMEDA J. Microstructure and mechanical properties of hot extruded Mg–Al–Mn–Ca alloy produced by rapid solidification powder metallurgy [J]. Materials and Design, 2010, 31: 2444–2453.
- [18] SU Gui-hua, ZHANG Liang, CHENG Li-ren, LIU Yong-bing, CAO Zhan-yi. Microstructure and mechanical properties of Mg–6Al–0.3Mn–xY alloys prepared by casting and hot rolling [J]. Transactions of Nonferrous Metals Society of China, 2010, 20(3): 383–389.
- [19] DU Y Z, ZHENG M Y, XU C, QIAO X G, WU K, LIU X D, WANG G J, LV X Y. Microstructures and mechanical properties of as-cast and as-extruded Mg–4.50Zn–1.13Ca (wt%) alloys [J]. Materials Science and Engineering A, 2013, 576: 6–13.
- [20] PURCEK G, SARAY O, KARAMAN I, KUCUKOMEROGLU T. Effect of severe plastic deformation on tensile properties and impact

toughness of two-phase Zn–40Al alloy [J]. Materials Science and Engineering A, 2008, 490: 403–410.

HUANG Cen. Microstructures and mechanical properties of a hot extruded Mg–4.45Zn–0.46Y–0.76Zr alloy plate [J]. Materials and Design, 2014, 53: 602–610.

[21] JI Da-wei, LIU Chu-ming, TANG Lie-chong, WAN Ying-chun,

往复挤压对 AA 6061/SiC 复合材料力学性能的影响

Veysel ERTURUN¹, M. Baki KARAMIŞ²

1. Faculty of Aeronautics and Astronautics/Airframes and Powerplants, Erciyes University, Kayseri 38039, Turkey;

2. Department of Mechanical Engineering, Erciyes University, Kayseri 38039, Turkey

摘 要: 使用往复挤压(RE)方法改善铸造和粉末冶金(PM)法制备的铝基复合材料的力学性能。分别使用 AA 6063 铸件和 AA 6061 粉末作为基体, 使用 5% SiC(体积分数)颗粒作为增强相制备复合材料。挤压样品的硬度和晶粒尺寸随挤压道次的增加而降低, 而韧性和延展性随挤压道次的增加而增加。由于挤压样品的拉伸强度降低, 其伸长率增加。因此, 往复挤压是一种改善金属基复合材料(MMC)力学性能的有效方法。

关键词: 往复挤压; 金属基复合材料; 铝合金; 力学性能

(Edited by Mu-lan QIN)