Recent Research on the Deformation Behavior of Particle Reinforced Magnesium Matrix Composite: A Review

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Abstract

Particle reinforced magnesium matrix composite (PMMC) possesses the merits of high specific strength, high specific modulus, better dimensional stability, good wear resistance and lower production cost, which is thought as a promising material in the field of aerospace, automobile, electronic communication, etc. To eliminate the casting defect, the PMMC is usually experienced hot deformation process. The present paper mainly focuses on the deformation behavior of PMMCs. First, the development of PMMCs based on particle size is introduced. Then, the hot deformation technology and deformation mechanism of PMMCs at elevated temperature are given and analyzed, respectively. After reviewing the dynamic recrystallization and texture of PMMCs, its future development is suggested based on the current research progress.

Keywords Magnesium matrix composite · Particle · Hot deformation · Deformation mechanism · Recrystallization

1 Introduction

As the lightest metal structural material available in nature, magnesium alloy had attracted much more attention in the field of aerospace, automobile, electronic communication, etc [1–4]. However, the low modulus, low wear resistance, high coefficient of thermal expansion and poor high-temperature performance of magnesium alloy limit its application in industrial engineering. Particle reinforced magnesium matrix composites (PMMCs) not only have the advantage of magnesium alloy, but also possess the merits of high specific strength, high specific modulus, better dimensional stability, good wear resistance and lower production cost, which are thought as a promising material in the field of light weight [5–7].

The PMMCs can be processed by a variety of ways, such as power metallurgy [8, 9], in situ reaction [10, 11], spray

forming [12], squeeze casting [13] and stir casting [14, 15]. To eliminate the casting defect, the PMMCs are usually deformed by forging, extrusion, rolling, etc. During these processes, the grains are refined and the particle distribution is improved simultaneously, both of which contribute to the improved strength of PMMCs. It is known that dynamic recrystallization (DRX) occurs during hot deformation process. The existence of harden particle can not only influence the occurrence of DRX but also affect the deformation behavior of PMMCs. Thus, a large number of researchers have been intrigued in this aspect of PMMCs. This paper cannot include all the research aspects of PMMCs. Considering the fabrication process of PMMCs has been summarized in detail by Chen and Yao's work [16], the present work mainly focuses on the deformation technology, hot deformation mechanism, DRX behavior and prospects of PMMCs.

2 Development of PMMCs Based on Particle Size

In general, the mechanical properties of PMMCs strongly depend on the particle size, upon which the PMMCs can be divided into nano-, submicron and micron particle reinforced magnesium matrix composite, respectively.

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Owing to the easy fabrication process, the research of micron PMMCs began much earlier than nano- and submicron PMMCs. Cai et al. [17] fabricated the 15 vol% 10 μm SiC_p/Mg composite through stir casting technology, and it was found that most of the SiC_p distributed along grain boundaries and only a little amount (3 vol%) of them located at the interior of grains. Nevertheless, Cai et al. [17] pointed out that the thermal expansion could be generated between micron SiC_p and Mg matrix due to the different thermal expansion coefficients, which originated from the heterogeneous nucleation of Mg during solidification process. Wang et al. [15, 18] also fabricated micron $\text{SiC}_p/\text{AZ91}$ composite by stir casting technology, and the micron SiC_p was found at grain boundaries with “necklace” distribution. Such kind of particle distribution was thought easy to generate stress concentration and resulted in the initiation of microcrack

[15, 18]. As a conclusion, the “necklace” particle distribution and weaker interfacial bonding between SiC_p and Mg were responsible for the undesirable mechanical properties of PMMCs fabricated by stir casting technology [15, 18]. Subsequently, the researchers tried to ameliorate the manufacturing process of PMMCs for improving the mechanical properties of micron PMMCs. As compared with conventional stir casting, the compound casting was thought as an effective way to improve the mechanical properties of PMMCs [19]. In the latest work of Wang et al. [20], the combination of semisolid stirring casting and ultrasonic dispersion was used to fabricate the micron PMMCs. It was found that the compound casting methods had obvious effect on the improvement of the particle distribution and the increases of the yield strength (YS) and ultimate tensile strength (UTS) of PMMCs [20], as shown in Table 1.

Table 1 Tensile properties of PMMCs obtained from reference

Materials	YS (MPa)	UTS (MPa)	Modulus (GPa)	Elongation (%)	References
AZ91	~75	~128	~46	~2.05	[20]
5 vol% 10 μm $\text{SiC}_p/\text{AZ91}$	~110	~131	~50	~1.6	[20]
10 vol% 10 μm $\text{SiC}_p/\text{AZ91}$	~120	~172	~55	~1.4	[20]
15 vol% 10 μm $\text{SiC}_p/\text{AZ91}$	~145	~200	~62	~1.15	[20]
20 vol% 10 μm $\text{SiC}_p/\text{AZ91}$	~169	~192	~71	~0.6	[20]
25 vol% 15 μm $\text{SiC}_p/\text{AZ91}$	~310	~330	~78	~0.8	[21]
25 vol% 52 μm $\text{SiC}_p/\text{AZ91}$	~290	~340	~79	~1.1	[21]
20 vol% 15 μm $\text{SiC}_p/\text{AZ91}$	~330	~390	~71	~1.3	[21]
20 vol% 52 μm $\text{SiC}_p/\text{AZ91}$	~270	~320	~72	~1.1	[21]
1 vol% 60 nm $\text{SiC}_p/\text{AZ91}$	~85	~180	—	~5	[24]
0.5 wt% 60 μm $\text{Al}_2\text{O}_3/\text{Mg}$	~169	~232	~42.5	~6.5	[25]
1.5 wt% 60 μm $\text{Al}_2\text{O}_3/\text{Mg}$	~191	~247	~43.4	~8.8	[25]
2.5 wt% 60 μm $\text{Al}_2\text{O}_3/\text{Mg}$	~194	~250	~44.5	~6.9	[25]
0.35 vol% (45~55 nm) SiC_p/Mg	~116	~169	—	~5.2	[26]
0.5 vol% (45~55 nm) SiC_p/Mg	~107	~161	—	~6.5	[26]
1.0 vol% (45~55 nm) SiC_p/Mg	~125	~181	—	~6.1	[26]
3 vol% 1 μm $\text{SiC}_p/\text{AZ91}$	~99	~150	—	~2	[29]
5 vol% 1 μm $\text{SiC}_p/\text{AZ91}$	~108	~140	—	~0.8	[29]
0.5 vol% (32~36 nm) $\text{Y}_2\text{O}_3/\text{Mg}$	~141	~223	—	~8.5	[31]
1 vol% (32~36 nm) $\text{Y}_2\text{O}_3/\text{Mg}$	~151	~222	—	~6.8	[31]
2 vol% (32~36 nm) $\text{Y}_2\text{O}_3/\text{Mg}$	~162	~227	—	~7.0	[31]
1.5 wt% 36 nm $\text{Al}_2\text{O}_3/\text{Mg}$	~214	~261	—	~12.5	[34]
2.5 wt% 36 nm $\text{Al}_2\text{O}_3/\text{Mg}$	~200	~256	—	~8.6	[34]
5.5 wt% 36 nm $\text{Al}_2\text{O}_3/\text{Mg}$	~222	~281	—	~4.5	[34]
1 vol% 0.2 μm $\text{SiC}_p/\text{AZ91}$	~275.3	~335.4	~45.5	~2.43	[37]
1 vol% 0.2 μm + 9 vol% 10 μm $\text{SiC}_p/\text{AZ91}$	~328.8	~360.1	~61	~1.28	[37]
10 vol% 10 μm $\text{SiC}_p/\text{AZ91}$	~283.1	~347.6	~60.2	~1.18	[37]
1 vol% 60 nm + 14 vol% 10 μm $\text{SiC}_p/\text{AZ31B}$	~210	~295	—	~6.5	[38]
1 vol% 60 nm + 9 vol% 10 μm $\text{SiC}_p/\text{AZ31B}$	~225	~305	—	~3.9	[38]
1 vol% 60 nm + 4 vol% 10 μm $\text{SiC}_p/\text{AZ31B}$	~275	~350	—	~3.1	[38]
5.6 wt% Ti/Mg	~158	~226	—	~8	[40]
5.6 wt% Ti + 2.5 wt% $\text{B}_4\text{C}/\text{Mg}$	~215	~260	—	~8.1	[40]

The micron particles can play a significant role in improving the modulus and strength of PMMCs, but reduced the elongation of Mg matrix [21]. The decreasing size of micron particle can not only improve the strength of PMMCs but also lead to the increase in elongation. A little amount of micron (1–2 μm) SiC_p was added into AZ91 alloy by Chen et al. [22], and then the PMMCs with finer grains as well as the better strength and ductility were obtained. As the particle size is finer than 1 μm , the interfacial bonding between the particle and Mg matrix becomes well owing to the less surface defects around the particles, which will strengthen the load transfer effect. In particular, the nanoparticles usually exhibit excellent strengthening effects due to their unique scale effects [23, 24]. The investigation of Hassan et al. [25] proved that the Mg with 0.66 vol% and 1.11 vol% nano-Al₂O_{3p} possess the higher YS and UTS than that with high content micron particles.

In addition, it was found that the nanoparticles can not only increase the strength of Mg matrix but also improve its plasticity remarkably [25–28]. The combination of semi-solid stirring casting and ultrasonic dispersion method was adopted to fabricate nano-SiC_p/AZ91 composite, and the results indicated that the composite not only possess uniform nanoparticle distribution but also own high strength and desirable ductility [29]. The main strengthening mechanisms of nano-PMMC were classified as Orowan strengthening and fine grain strengthening according to the investigation on nano-Al₂O_{3p}/Mg composite [30]. Moreover, Goh et al. [31] found that the nanoparticles can not only improve the mechanical properties but also enhance the thermostability of Mg alloy. Nevertheless, Radi et al. thought that the contribution of nanoparticles to the high-temperature microstructure stability of Mg matrix derives from their pinning effect on grain boundaries and hindering effect on dislocation movement [32].

Apart from adding particles, the TiC_p with the size of 3–7 nm were obtained by Hwang and Nishimura [33] through chemical reaction of Ti and C powder. Then, the nano-TiC_p/Mg composite with better strength and ductility was obtained [33]. However, considering the high cost of nanoparticles, some researchers carried out the exploration of submicron PMMCs. Hassan et al. [34] studied the effect of submicron Al₂O_{3p} on the microstructure and tensile properties of Mg matrix and found that the strengthening effect of submicron Al₂O_{3p} was better than that of nanoparticles. Deng et al. [35] fabricated the submicron SiC_p/AZ91

composite through stir casting, and the results proved that the submicron SiC_p can improve the mechanical properties of AZ91 significantly. However, the strengthening effect of submicron particle on Mg matrix depends on its volume fraction. Deng et al. [35] found that the severe submicron particle agglomeration appeared and the strength of submicron PMMCs decreased once the volume fraction of submicron SiC_p was higher than 2%. The research of Ferkel et al. on nanoparticles also confirmed that the effective volume fraction of submicron particle was no more than 2% [36].

The elastic modulus of PMMCs is closely related to particle content. The higher particle content in PMMCs exhibits the higher modulus of PMMCs. Although nano- and submicron particles can greatly enhance the strength and ductility of Mg matrix, the higher volume fraction of nano- or submicron PMMCs is difficult to fabricate. Therefore, the single-sized nano- or submicron particles usually make a little contribution to the modulus of PMMCs. To give full play to the strengthening effects of different sized particles, Deng et al. [37] fabricated PMMCs with bimodal-sized particles through mixing 1 vol% submicron SiC_p and 9 vol% micron SiC_p, the tensile properties of which are given in Table 2. It shows clearly that the PMMCs with bimodal-sized particles exhibit better tensile properties than those with single-sized particles. Shen et al. [38] also fabricated bimodal-sized PMMCs through mixing nano- and submicron particles, and then the same conclusions as Deng et al. were also obtained. Recently, Sankaranarayanan et al. fabricated (nano-SiC_p + micron Ti_p)/Mg [39] and (nano-B₄C_p + micron Ti_p)/Mg [40] composite, and the similar results were obtained showing that the bimodal-sized PMMCs possess better mechanical properties than the PMMCs with single-sized particle.

3 Hot Deformation Technology of PMMCs

Usually, only basal slip system (0001) $\langle 11\bar{2}0 \rangle$ can occur in Mg at room temperature [41]. As the limited slip system, the plasticity of Mg is poor. At high temperature, apart from basal slip system, prismatic slip system $\{10\bar{1}0\} \langle 11\bar{2}0 \rangle$ and pyramidal slip system $\{10\bar{1}1\} \langle 11\bar{2}0 \rangle$ can operate, both of which contribute to the higher plastic deformation ability of Mg. Nevertheless, the PMMCs will possess fine grains, uniform particle distribution and higher mechanical properties after being deformed at high temperatures. The common

Table 2 Mechanical properties of the SiC_p/AZ91 composites after hot deformation. Reproduced from [37], with permission from Elsevier

Materials	YS (MPa)	UTS (MPa)	Modulus (GPa)	Elongation (%)
0.2 μm 1%	275.3 $\pm$ 5.2	335.4 $\pm$ 4.3	45.5 $\pm$ 0.72	2.43 $\pm$ 0.55
0.2 μm 1% + 10 μm 9%	328.8 $\pm$ 1.9	360.1 $\pm$ 2.2	61 $\pm$ 0.76	1.28 $\pm$ 0.05
10 μm 10%	283.1 $\pm$ 5.1	347.6 $\pm$ 5.2	60.2 $\pm$ 2.23	1.18 $\pm$ 0.27

deformation methods used on PMMCs include ECAP, forging, extrusion and rolling, etc.

3.1 Equal Channel Angular Pressing

Equal channel angular pressing (ECAP) refers to a process in which material is subjected to strong shear deformation at the corner of the mold, and the cross-sectional dimensions remains basically unchanged. Hence, it can be conducted repeatedly and accumulated a larger strain. A lot of works have been carried out about the effect of ECAP on Mg alloy [42–49]. The results revealed that both the strength and ductility of Mg alloy can be greatly improved after the application of ECAP process owing to obvious grain refinement. According to the paths during ECAP process, the ECAP can be executed through four ways: path A, path Bc, path Ba and path C. Previous work showed that the ECAP paths have significant effect on the start of slip system, grain refinement, morphology and distribution of the phase, all of which would directly related to the material's mechanical properties [50–53].

Currently, the ECAP process is mainly applied on Mg alloy, and there are only a few researches on PMMCs processed by ECAP. Jia et al. [54] carried out ECAP on the $\text{Mg}_2\text{Si}_p/\text{ZK60}$ composites, the results indicated that the UTS was increased from 154.8 to 270 MPa, and the elongation was improved from 4.5 to 17.5% after four passes of ECAP. Gan et al. [55] performed ECAP on the in situ $\text{Mg}_2\text{Si}_p/\text{Mg}$ composites and found that the grain of Mg matrix was refined and the intensity strength of (0002) basal plane texture was weakened after the application of ECAP process. However, it was interesting to note that the grain size of Mg matrix changed a little during the subsequent ECAP process [55].

3.2 Forging

Pervious work has confirmed that the PMMCs could also be deformed by forging process. Deng et al. [56] forged 10 μm 10%SiCp/AZ91 composite with the deformation strain of 50% at different temperatures. Then, the effect of forging temperature on the particle distribution, grain size, texture and tensile properties of the SiCp/AZ91 composites was investigated, and the best primary forging temperature for SiCp/AZ91 composites was 420 °C [56]. Subsequently, the further work of Deng et al. focused on the effect of forging strain on the SiCp/AZ91 composite at the forging temperature of 420 °C [57]. Results demonstrated that the texture intensity increased significantly accompanied with increasing forging stain; however, the tensile properties were deteriorated as the strain increased from 60 to 80% owing to the occurrence of SiCp's agglomeration [57]. Above

phenomenon indicated that the PMMCs are sensitive to both the temperature and strain during one-step forging process.

Besides one-step forging, the multidirectional forging (MDF) was applied to nano-SiCp/AZ91 composite by Nie et al. [58], and they found that the grain size of the composite was refined after one-step MDF. However, the grain size was not decreased monotonously with increasing MDF passes, and the grains grew up inversely after 3 passes of MDF. The authors thought that both the strain accumulation and nucleation driving force increased with increasing MDF passes, which would resulted in the increase in both nucleation rate and growth rate of the DRXed grain. Once the growth rate of DRXed grain is larger than that of nucleation rate, the average size of DRXed grain will grow up. After the application of MDF, the tensile strength of nano-SiCp/AZ91 composites was improved significantly, which was attributed to grain refinement and Orowan strengthening according to the investigation of Nie et al. [58].

Moreover, cyclic die forging (CCDF) was performed on nano-SiCp/Mg matrix composite in recent years [59]. After forging at 400 °C for 3 passes, the grain size was decreased to ~2.5 μm accompanying with the disappearance of $\text{Mg}_{17}\text{Al}_{12}$ phase. As the forging temperature decreased to 300 °C, the $\text{Mg}_{17}\text{Al}_{12}$ phase precipitated again and the grain size was refined to ~650 nm after twice CCDF [59]. Simultaneously, the application of CCDF was also propitious to the distribution of nano-SiCp leading to the better YS and UTS of nano-PMMC [59]. The nano-SiCp/AZ91 composites were performed through CCDF by Guo et al. [60], they found that the grains of Mg matrix were remarkably refined, and the strength as well as elongation was both improved significantly after 5 passes. During the CCDF process, the agglomerated nano-SiCp was broken by matrix flow and distributed dispersive in the Mg matrix; however, the nano-SiCp agglomeration region cannot be completely eliminated due to the high surface energy of nano-SiCp [60]. In addition, the AZ31-Si composite was also forged through CCDF by Guo et al. [61], and they found that the Mg_2Si particle was broken under the shear stress of matrix during forging process. Accompanied with increasing CCDF pass, the grain was refined and the distribution of Mg_2Si became more uniform, both of which contributed to the improvement in mechanical properties [61].

3.3 Extrusion

As a conventional hot deformation process, extrusion has been used widely in PMMCs. Wang et al. [62] performed hot extrusion on 10 μm SiCp/AZ91 composites at 350 °C, and they found that the particle agglomeration disappeared and the grains were refined, both of which resulted in the improved mechanical properties of micron PMMCs. Besides, increasing volume fraction of SiCp was beneficial

to grain refinement as well as the improvements in strength and elastic modulus, but reduce the elongation of Mg matrix [62]. Nevertheless, Wang et al. [63] also found that the hot extrusion could cause the crack of SiCp and the interfacial debonding between SiCp and Mg matrix, which inevitably deteriorated the strength of the SiCp/AZ91 composite with high volume fraction (20 vol%). The same phenomenon has also been obtained by the research on 10 μm SiCp reinforced Mg–Zn–Ca composite [64]. Besides volume fraction, the particle size also had significant effect on the microstructure and mechanical properties of the as-extruded PMMCs based on the investigation of SiCp/Mg–Al–Ca composite [65]. The results revealed that the size of SiCp could influence the shape and distribution of precipitated phase, and the most excellent mechanical properties were obtained when the size of SiCp is 5 μm .

To eliminate the secondary phase and improve the high-temperature deformation ability of PMMCs, it was usually solution-treated prior to hot extrusion. Shang et al. [66] attempted to extrude the as-cast 5 μm 10 vol% SiCp/M–Al–Zn composite directly at 320 °C, and then the obtained YS, UTS and elongation of the composite were ~310 MPa, ~395 MPa and 3.8%, respectively. It was believed that the refinement of both $\text{Mg}_{17}\text{Al}_{12}$ phase and grain size were responsible for the high comprehensive mechanical properties caused by hot extrusion [66].

Sun et al. [67] considered that the high content of $\text{Mg}_{17}\text{Al}_{12}$ phase was the main reason for the excellent mechanical properties of SiCp/M–Al–Zn composites. To obtain the fine-grained PMMCs with high content of $\text{Mg}_{17}\text{Al}_{12}$ phase, they attempted to extrude 5 μm 10 vol% SiCp/AZ91 with lower extrusion speed (0.01–1 mm/s) at 250 °C [67]. At last, the PMMCs with the DRXed grain size of ~0.5 μm and the volume fraction of $\text{Mg}_{17}\text{Al}_{12}$ phase of 16–18 vol% were obtained [67]. The interaction between SiCp and DRX was responsible for the high content of $\text{Mg}_{17}\text{Al}_{12}$. As the decrease in extrusion speed, the

tensile strength of PMMCs increased, but the elongation of which was decreased [67]. When the extrusion speed drops to 0.01 mm/s, the YS and UTS could reach to ~391 MPa and ~440 MPa, respectively, as shown in Fig. 1, which are superior to the existing research levels [67]. The nano-SiCp/AZ91 composites were extruded by Nie et al. [68], and the results were similar to those of micron PMMCs. Above research indicated that the application of extrusion had obvious effect on grain refinement and improvement of particle distribution, both of which directly play a role in the improvement of YS and UTS of PMMCs.

3.4 Rolling

At present, only a few researches focused on the rolling behavior of PMMCs. Considering the nano-PMMC with low particle content possessed better ductility, the nano-PMMC were rolled firstly by the investigators. The 1 vol% nano-SiCp/AZ31 composite was rolled by Liu et al. [69] at 350 °C with 15% reduction per pass, and the results showed that the grain size was refined and the distribution of nano-SiCp became much more uniform with increasing rolling pass. After 11 passes, the YS was more than twice the as-cast conditions, but the YS and UTS anisotropy existed between parallel and vertical rolling directions [69]. Subsequently, Wang et al. [70] further explored the effect of 1 vol% nano-SiCp on the microstructure and mechanical properties of AZ31 alloy during rolling, and they found that nano-SiCp can effectively inhibit the formation of shear bands and influence the texture strength of Mg matrix. At the same time, due to the inhibitory effect of nano-SiCp on the growth of DRXed grains, the regions with fine grains were formed in the nano-PMMC, while the grains were large among these fine-grained regions [70]. This kind of bimodal-sized grains in the as-rolled nano-PMMC was thought propitious to the improvement in mechanical properties.

Fig. 1 Comparison of mechanical properties among SiCp/AZ91 composites extruded with different speeds and other AZ91 matrix composites reinforced with SiCp: **a** YS, **b** UTS. Reproduced from [67], with permission from Elsevier

The microstructure evolution mechanism of (0.1–3 μm) $\text{YAl}_{2\text{p}}/\text{MgLiAl}$ composites during rolling process was conducted, and it was found that the distribution of $\text{YAl}_{2\text{p}}$ became much more uniform with increasing reduction amount of rolling [71]. Besides, the fragmentation of $\text{YAl}_{2\text{p}}$ was also found at the same time. Nevertheless, the precipitation of α phase in MgLiAl matrix was observed during the rolling process. The interface between α phase and β matrix belonged to semi-coherent, and the existed specific orientation relationship was $(0002)_{\alpha} // (110)_{\beta}$ [71]. Beside α phase, the precipitated YAl particles were also found [71], which might be originated from the reaction between Y element in $\text{YAl}_{2\text{p}}$ and Al element in MgLiAl matrix.

3.5 Two-Step Deformation

The two-step hot deformation process is a common method for refining grain size and improving mechanical properties of Mg alloys. As compared to the one-step extrusion or ECAP, the grains of Mg -0.6% Zr alloy were significantly refined ($\sim 1 \mu\text{m}$) after two-step deformation (extrusion + ECAP) [72]. Moreover, the super-plasticity of Mg -0.6% Zr alloy after two-step deformation was investigated by Matsubara et al. [47], the results showed that the elongation of Mg -0.6% Zr alloy could reach 400% at 100 $^{\circ}\text{C}$, which demonstrated good high-temperature plasticity. After subjecting the two-step deformation (extrusion + ECAP) to AZ31 alloy, the same results were also obtained by Stráská et al. [73]. The investigation of Ying et al. on ZK60 alloy showed that the basal plane texture was weakened and the YS was low after one-step ECAP; however, the grains were refined to $\sim 1 \mu\text{m}$, and the YS and UTS are increased to 342 MPa and 388 MPa, respectively, after the subsequent extrusion process [74].

Based on the investigation of two-step deformation on Mg alloy, the researchers began to apply two-step deformation on PMMCs. Wu et al. [75] carried out two-step hot deformation (forging + extrusion) on 5 μm 10 vol% $\text{SiCp}/\text{AZ91}$ composites, and the results showed that the grains became much finer and the SiCp distributed much uniform after two-step deformation. Deng et al. [76] adopted the same two-step hot deformation as Wu et al. on 0.2 μm 1.5 vol% $\text{SiCp}/\text{AZ91}$ composites, and the similar results were also obtained in submicron PMMCs. Recently, the nano- $\text{SiCp}/\text{AZ91}$ composite was fabricated through stirring casting by Qiao et al. [77], and then it was performed by hot extrusion and ECAP subsequently. The results confirmed that the application of two-step deformation was helpful to grain refinement, particle distribution as well as weakening basal plane texture of nano-PMMC, all of which contributed to the improvement in YS and UTS .

4 Deformation Mechanism of PMMCs

The flow stress is closely related to temperature and strain rate for the material deformed at high temperature. The constitutive equation based on the relationship among flow stress, strain rate and temperature has important guiding significance for the material's hot deformation process. At present, the three constitutive equations of power, exponential and hyperbolic sinusoids are mainly used to reveal the high-temperature deformation behavior of materials. Based on the above constitutive equation, the stress index n and the deformation activation energy Q of the material under high-temperature deformation can be calculated. According to the n and Q values, the deformation mechanism of the material can be illustrated [78–83].

The micron PMMC (10 μm 10 vol% $\text{SiCp}/\text{AZ91}$ composite) was compressed at 250–400 $^{\circ}\text{C}$ by Wang et al. [84], and the results showed that both the peak stress and flow stress decreased with increasing temperature and strain rate. Based on the high-temperature compression curve analysis, the calculated n and Q were 5 and 99 kJ/mol, respectively, which was considered that the high-temperature deformation mechanism of this kind of PMMCs was the dislocation climbing mechanism controlled by grain boundary diffusion. The microstructure evolution of this kind of 10 μm 10 vol% $\text{SiCp}/\text{AZ91}$ composite compressed at high temperature was also researched [85]. It revealed that the high-temperature compression was beneficial to improve the distribution of SiCp . Moreover, the compression temperature and strain rate could affect the generation of dislocations and twins and finally influenced the DRX behavior of micron PMMCs.

In addition to micron PMMCs, the researchers also carried out related research on the high-temperature deformation behavior of nano-PMMC. Wang et al. [86] prepared nano- $\text{SiCp}/\text{AZ91}$ composite by a combination of stirred casting and ultrasonic dispersion. After analyzing the compression curves of nano- $\text{SiCp}/\text{AZ91}$ composite at 250–400 $^{\circ}\text{C}$, the deformation activation energy Q was calculated to be $\sim 185 \text{ kJ/mol}$ [86], which was higher than the self-diffusion activation energy of pure magnesium (135 kJ/mol) [87]. The deformation mechanism of nano- $\text{SiCp}/\text{AZ91}$ composite was thought as the dislocation climbing mechanism controlled by self-diffusion [86]. Further research of Nie et al. found that the addition of nanoparticles could also improve the deformation ability of AZ91 alloy under high-temperature conditions [88].

Prasad et al. [78] performed high-temperature compression on the as-extruded 1 vol% nano- $\text{Al}_2\text{O}_3/\text{Mg}$ composite at 300–500 $^{\circ}\text{C}$ and found that the optimum deformation conditions were located at 400–450 $^{\circ}\text{C}$ with the strain rate larger than 0.1 s^{-1} . In addition, the deformation activation

energy of $\text{Al}_2\text{O}_3/\text{Mg}$ composites was also related to strain rate. At high strain rates, the Q values of both Mg alloys and nano-PMMCs were close to the grain boundary diffusion activation energy (92 kJ/mol), and the deformation behavior was influenced by grain boundary diffusion. At the low strain rate, the Q values of Mg alloy and nano-PMMCs were 136 kJ/mol and 305 kJ/mol, respectively, which were larger than the self-diffusion activation energy of pure magnesium (135 kJ/mol), and the deformation behavior of which was thought to be controlled by lattice self-diffusion [78].

The 1.5 vol% nano-Al/AZ31 material was fabricated by Zhong et al. [82] through DMD process. After being extruded, the high-temperature deformation behavior of the above nano-PMMCs was analyzed. Results indicated that the grain boundary sliding still played a main role in the fine-grained PMMCs, while the existence of nanoparticles had a certain hindrance to grain boundary sliding. The 17 vol% 2 μm SiCp/ZK60 composite prepared by powder metallurgy was extruded by Watanabe et al. [89], and then the grain size of only $\sim 1.7 \mu\text{m}$ was obtained. After being subjected to tensile at 175–228 $^{\circ}\text{C}$, the deformation activation energy was calculated to be 97 kJ/mol, which was close to the grain boundary diffusion activation energy of pure magnesium [89]. Therefore, the deformation mechanism of 17 vol% 2 μm SiCp/ZK60 composite at low temperatures was considered to be grain boundary sliding mechanism controlled by grain boundary diffusion.

In general, the grain boundary sliding occurs much more easily with decreasing grain size, resulting in the reduction in deformation energy. As the particle existed in the Mg matrix, the deformation mechanism is inevitable changed owing to the variation of DRX behavior influenced by particle size. Even though some works have been done on the fine-grained PMMCs, the high-temperature deformation behavior of fine-grained PMMCs influenced by particle size and their coupling effect still need further investigation.

5 DRX Behavior of PMMCs

Generally, the dynamic recrystallization (DRX) of Mg alloy is absolutely different from that of static recrystallization. The main difference between them is the driving force. The driving force relates to the stored energy in Mg alloy during deformation process. The release of stored energy promotes the movement of dislocations and grain boundaries, which is helpful to the nucleation and growth of recrystallized grains. For static recrystallization, the stored energy decreases gradually during recrystallization process, and the nucleation of recrystallized grains will be stopped once the stored energy is used up. On the contrary, the stored energy of DRX will be provided continuously, which lead to the

continuously occurrence of the DRXed nucleus during the whole hot deformation process.

As the harden particles existed in the Mg alloys, more dislocations can be generated during deformation process due to the deformation mismatch between the particles and Mg matrix. Meanwhile, the existence of particles also makes it hard for the movement of dislocations and grain boundaries. Thus, the recrystallization behavior of Mg alloy containing harden particles should be different from that of monolithic Mg alloy. The research has illustrated that the recrystallization behavior of PMMCs depends on particles size.

(1) Large particles ($> 1 \mu\text{m}$)

As the size of harden particle is larger than 1 μm , the region with high-density dislocation and large orientation gradient can be formed in the vicinity of particle owing to the deformation mismatch between the particle and matrix, which is recognized as particle deformation zone (PDZ) [90, 91]. According to Ref. [89], the size of PDZ around harden particles is approximately 1.5–1.8 times of the particle size. Figure 2 [92] shows the schematic of PDZ. Due to the high storage energy in PDZ, the nucleation of recrystallization can be promoted and this phenomenon was called as particle stimulated nucleation (PSN) mechanism [90, 91]. Regarding the PSN mechanism, a lot of researches have been carried out on aluminum matrix composites, and it was the large misorientation in PDZ and faster migration rate of the sub-grain boundary around particles favorable for the formation of new large-angle grain boundaries [93, 94]. Besides, the misorientation was large among recrystallized grains formed

Fig. 2 Schematic of particle deformation zone (PDZ). Reproduced from [92], with permission from Elsevier

through PSN, which was also beneficial to adjusting the texture of material [91].

During the recrystallization process, a stable recrystallization core can be developed only when the recrystallized core reaches a critical nucleation radius and the misorientation between adjacent grain boundaries is greater than 10° . Moreover, the occurrence of recrystallization is also related to the deformation temperature and strain rate. In general, the recrystallized nucleation is more likely to occur accompanying with increasing temperature and decreasing strain rate. Based on the investigation of SiC_p reinforced AZ91 composite, the DRXed rate of PMMCs during hot deformation was higher than that of monolith matrix alloy. This was contributed to the PDZ formed around micro- SiC_p during hot deformation, which was helpful to promote the nucleation of DRXed grains. PDZ is about one diameter along the interface between particle and Mg matrix, which enlarges with increasing size of SiC_p [95].

In addition, Wang studied the effect of necklace-like particle distribution on DRX behavior, and the results showed that the DRXed grains mainly distributed along SiC_p in the shape of a necklace at grain boundaries, as shown in Fig. 3 [96]. With the proceeding of hot deformation, the extent of DRX increased and it extended to the entire matrix gradually. As the promoting effect of micron particle on the nucleation of DRXed grains, the micron PMMCs usually possessed fine grains as compared to monolithic Mg alloy [65, 97, 98].

(2) Fine particles ($< 1 \mu\text{m}$)

The size of PDZ strongly depends on particle size, thus the PDZ size is very small, and its promotion effect on recrystallization nucleation is negligible as the particle size is finer than $1 \mu\text{m}$. Prasad et al. [78] thought that the fine particles had a strong pinning effect on grain boundary, so the grain boundary was not easy to slip, rotate and migrate, and this nearly does not change the grain size in Mg matrix during hot deformation process. Even though the fine particles had a little effect on the volume fraction of DRXed grains, Robson et al. [99] found that the recrystallization process in Mg matrix could be delayed when it is deformed at low strain rate. Chan et al. [100] also found that the fine particles had the pinning effect on both the low-angle grain boundaries and high-angle grain boundaries, especially in the initial stage of recrystallization. Then, they thought the fine particles had the hinder effect on the nucleation of recrystallization in Mg matrix [100].

Pervious works have demonstrated that the fine particles had a certain inhibitory effect on recrystallized nucleation; however, the researches [30, 32, 87] on nano-PMMC [30] have shown that the fine particles could promote the nucleation of DRXed grains, which made the grains in Mg matrix remarkably be refined after hot deformation. Similar results were also obtained in submicron PMMCs, and it was thought that the fine particles could not only promote the generation of dislocations owing to deformation mismatch of the particles with matrix, but also lead to the increase of dislocation density due to their pinning effect on dislocations [37, 101]. So, the fine particles were thought propitious to the nucleation of DRXed grains and the corresponded DRXed

Fig. 3 Schematic diagram of the necklace DRX mechanism of Mg matrix composites with necklace-type particle distribution: **a** particles distribute along the grain boundaries; **b** PDZs are formed along grain boundaries; **c** DRX preferentially occurs along the initial grain

boundaries due to PSN; **d** DRX extends from intergranular areas of initial grains to initial transgranular areas; **e** DRX is completed. Reproduced from [96], with permission from Elsevier

mechanism influenced by fine particles was also proposed and is shown in Fig. 4 [37, 101].

6 Recrystallized Texture of PMMCs

Usually, DRXed texture can be formed in Mg alloy after hot deformation process, such as rolling, forging, and extrusion, etc. Thus, the influence of particles on DRX will inevitably act on the texture of Mg alloys. In fact, the research of the influence of particles on recrystallized texture has been noticed at the beginning of the investigation on particle reinforced Al matrix composite. At the initial stage of the research on this aspect, there was no consensus on whether the PSN could influence the recrystallized texture or not. According to the research of Ref [102], the texture became

more random and the texture intensity was weakened after the occurrence of recrystallization. Chan et al. [100] found that the texture intensity was strengthened after recrystallization, and then a typical recrystallized texture could be formed. The difference from work between Bleck et al. and Chan et al. may be derived from their different measurement methods for crystal orientation. The X-ray method adopted by Bleck et al. lacked accuracy. Nevertheless, the research of Chan et al. based on TEM observation was too microscopic to reflect the overall orientation characteristics of the sample. However, it was possible to directly observe the nucleation and growth stages of recrystallization by EBSD, which would give a clearer understanding to the evolution of recrystallized texture.

Habiby et al. [103] used EBSD technique to analyze the grain orientation before and after recrystallization, and the

Fig. 4 Schematic illustration of DRX influenced by submicron SiCp during hot deformation: **a** microstructure before DRX, **b** high-density dislocations around submicron SiC particles, **c** DRX nucleation pri-

ority near submicron SiC particles and at grain boundaries, **d** microstructure after DRX. Reproduced from [101], with permission from Elsevier

result indicated that the recrystallized texture was closely related to both the initial texture and orientation of recrystallized nucleus. It was believed that the influence of PSN on recrystallized texture depended on the recrystallized temperature [103]. At high temperature, recrystallization nucleated at the center of PDZ, and the formed texture was random. However, the nucleation was formed by the migration of subgrain boundary at low temperature, so the obtained recrystallized texture was similar to the initial texture of the material, which was consistent well with the results of Orsund et al. [104].

In recent years, related research on the recrystallized texture of PMMCs has also been carried out. Robson et al. [92] studied the Mg-Mn alloy containing micron particles and found that recrystallization mainly occurred inside the grains and PSN had a little effect on the recrystallized texture. Based on the research of the as-forged Mg alloys [105], the occurrence of PSN could weaken texture but not change the type of texture. Radi et al. [32] also obtained the same results in nano-PMMC, and it was believed that nano- Al_2O_3 particles could influence the intensity of recrystallized texture, but had no effect on changing the type of texture.

The recrystallized texture of PMMCs depends on the hot deformation technology. Both the monolithic AZ91 alloy and 10 μm 10 vol% SiCp/AZ91 composite were forged by Deng et al [56], and they found that the typical forging texture with the (0002) basal plane perpendicular to forging direction was formed after forging process, as shown in Fig. 5, and the existence of micron SiCp weakened the intensity of texture, but had no influence on the type of texture. On the subsequent work of Deng et al, the forged AZ91 alloy and PMMCs were extruded [95]; the result indicated that the (0002) basal plane was parallel to extrusion direction and the prismatic plane was perpendicular to the extrusion direction, as shown in Fig. 6. Besides, their results also revealed that the type of texture was independent of the particle size. Regardless of fine ($< 1 \mu\text{m}$) or large ($> 1 \mu\text{m}$) particles, both of them could not change the texture type, but only weakened the intensity of texture [95]. Even so, the weakening

effect of particles on texture intensity depended on particle size. Owing to the deformation mismatch between particle and matrix, the PDZ with high-density dislocation and large orientation gradient could be formed in the vicinity of the large particles ($> 1 \mu\text{m}$) during hot deformation process, which was propitious to the nucleation of recrystallization. After recrystallization, the texture was random in PDZ, which led to the weakening of texture intensity after hot deformation. Accompanying with decreasing particles size, the size of PDZ was also decreased, thus its effect on the nucleation of recrystallization was also weakened. As a consequent, the effect PDZ on weakening texture intensity was decreased.

7 Prospects

Introducing particles into Mg matrix aims to improve the Mg alloy's comprehensive mechanical properties, such as strength, modulus, elongation, dimensional stability, wear resistance. All the properties are related to the fabrication and hot deformation processing technology. Nevertheless, the particle size and volume fraction of PMMCs also play an important role. To obtain the PMMCs with comprehensive mechanical properties, the multi-scale particle reinforced Mg matrix composites become much more popular than those with single-sized particles. However, how to realize the uniform particle distribution and increase the amount of fine (nano- or submicron) particles in multi-scale PMMCs is still a question. Recent researches have shown that the nano-secondary phase precipitates in the Mg alloy or PMMCs during hot deformation process, and it also demonstrates that the micron PMMCs containing nano-precipitates processes better mechanical properties than the multi-scale PMMCs in the present research. So, processing the PMMCs by the combination of adding large particles and dynamic precipitated fine phase is promising way.

The dynamic precipitation process is accompanied with the occurrence of dynamic recrystallization in PMMCs

Fig. 5 Basal pole figures of the SiCp/AZ91 composite forged at **a** 320 °C, **b** 370 °C, **c** 420 °C. Reproduced from [56], with permission from Elsevier

Fig. 6 Pole figures of the **a** AZ91 alloy, **b** 0.2 $\mu\text{m}5\%$, **c** 10 $\mu\text{m}5\%$ SiCp/AZ91 composites after hot deformation. Reproduced from [92], with permission from Elsevier

during hot deformation process [106]. Moreover, the occurrence of dynamic recrystallization leads to the grain refinement, which will provide more grain boundaries and is propitious to the precipitation of secondary phase. On the contrary, the precipitated secondary phase can also influence the nucleation and growth of DRXed grains. It should be noted that the PDZ with high-density dislocation and large orientation gradient can be formed in the

vicinity of the large particles ($> 1 \mu\text{m}$) during hot deformation process, which is not only propitious to the nucleation of recrystallization, but also be helpful to the precipitation of secondary phase. Thus, it can be concluded that a closely associated relationship exists among precipitate, dynamic recrystallization and PDZ, all of which will inevitable reflect on the microstructure and mechanical properties of PMMCs after hot deformation. The relationship

among DRX, dynamic precipitation and PDZ in PMMCs still needs further investigation.

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