Results in Engineering 7 (2020) 100162

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.editorialmanager.com/rineng/Default.aspx

What is the major problem with wrought Mg alloys?

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ARTICLE INFO

Keywords
Cross pre-compression
Texture
Schmid factor
Pre-induced <c+a> slips
Strength and ductility

ABSTRACT

From a mechanistic point of view, eye-catching magnesium alloys are greatly different than face-centered cubic metals. However, low strength, low ductility, and anisotropic mechanical behavior of Mg alloys are main hurdles, which are mainly attributed to the hexagonal close-packed structure, limited-slip activity, low stacking fault energy, and twin strain path dependencies. The $\{10\bar{1}2\} < 10\bar{1}1 >$twin boundaries can easily be imparted in Mg alloys through in-plane compression, thereby decrease the grain size through twin boundaries grain refinement and greatly change the crystallographic texture. The twin dependencies on strain path loading and different slip activity change the mechanical strength. However, the size of the specimen before pre-compression is the most critical parameter which should be chosen wisely. Apart from this, a fraction of <c+a> dislocations can also be induced by pre-compression up to strain ~7–10%. Therefore, it is anticipated that the pre-induced grain refinement through twin boundaries, textural changes, and <c+a> dislocations by cross pre-compression would be advantageous for high strength, high ductility, and exacerbation of anisotropic behavior.

Magnesium (Mg) alloys are promising next-generation structural materials for the biomedical, aerospace, military, and automotive industry [1–3]. The density of the Mg (1.78 g cm^{-3}) is lower than the cupper [4,5], iron [6] steel [7–9], and aluminum [10,11]. The use of die-casted Mg alloys is greater than their wrought Mg counter-parts, but the strength of the die-casted Mg alloy is quite low, comparatively. However, during the last decade, extensive research has been conducted on wrought Mg alloys [12–17]. These alloys are susceptible to anisotropic mechanical behavior and prone to low ductility due to the limited-slip system offered by a hexagonal crystal structure (hcp). In Mg alloys, the plastic strain can only be accommodated by $1/\ 3 < 11\bar{2}3 >$ (<c+a>) slip system and preferentially operative twinning along with the [0001] axis. It is to note that the most frequently operative slip is the basal plane with $1/3 < 11\bar{2}0 >$(<a>) direction. The critical resolve shear stresses (CRSS) of the <c+a> is well documented and about 2–5 times higher than the <a> slip system. Most specifically <a> slip system can provide only two independent deformation modes, while <c+a> alone can provide 5 deformation modes and sufficient to fulfill the Von-misses criterion. Therefore, intense fiber texture and high CRSS of <c+a> slip lead to low ductility in Mg alloys. Besides, the difference of the slip systems and twinning along with different loading directions leads to mechanical anisotropy in Mg alloys. Grain refinement and emancipation of the twinning activity is one of the useful methods for exacerbation of anisotropic mechanical behavior. However, grain refinement through cost in-effective processes leads to low tensile yield strength owing to weak basal texture as evidence in Ref [18,19]. Another problem is strain hardening in ultrafine-grained intense basal textured wrought Mg alloys [20]. The twin dependencies on strain path loading and higher the twin interface nucleation energy with a decrease in grain size lead to low strain hardening. Therefore, grain refinement cannot be an exact solution for the isotropic mechanical behavior. In a previous investigation, it was revealed that the pre-induced <c+a> dislocation can enhance the ductility of the Mg alloys [21]. Here we proposed that cross pre-compression of the wrought Mg alloys sheet but for the specimen of the same dimension i.e., (30 mm × 30 mm × 30 mm) can be a practical technique for increasing the strength and ductility, without losing the large decrease in the tensile yield strength.

Firstly, the grain size of the Mg alloy should be greater than 15 μm and the dimension of the alloys should be the same; for example $50\,mm \times 50\,mm \times 50\,mm$. With the decrease in the grain size the twinning interface energy increased significantly, therefore twinning cannot be induced in fine grain size and hence the texture cannot be changed through twin boundaries [22]. Secondly, the extruded/rolled Mg alloy pre-compressed along extruded/rolled direction to introduce twin

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https://doi.org/10.1016/j.rineng.2020.100162
Received 31 July 2020; Received in revised form 9 August 2020; Accepted 10 August 2020

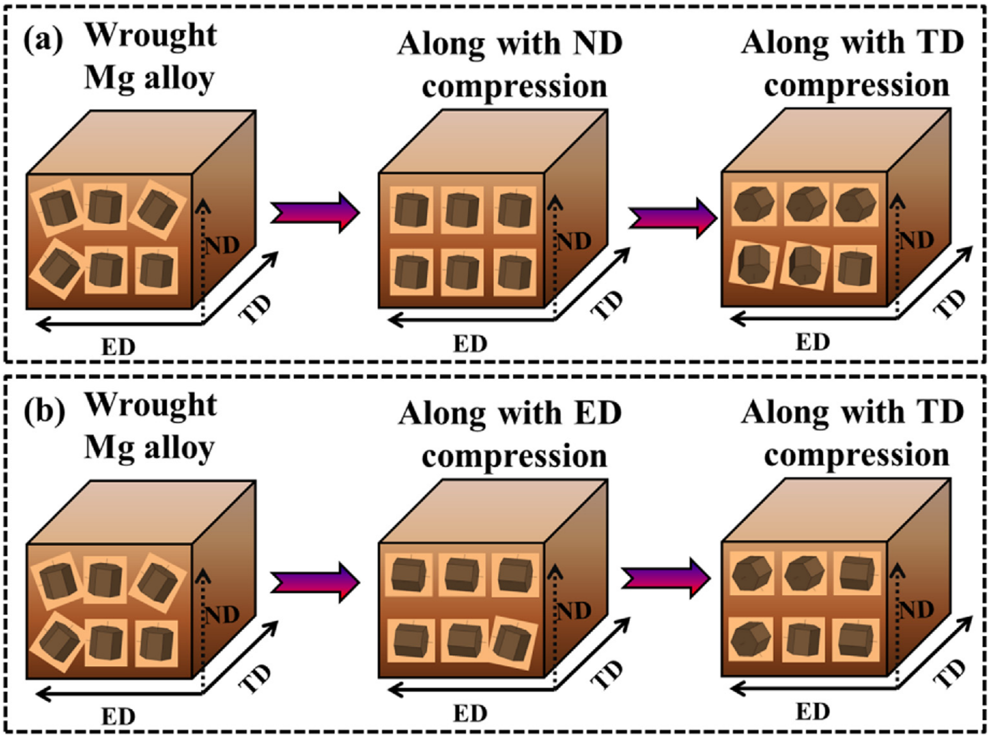

Fig. 1. The schematic illustration of the effect of different path loading on the crystallographic orientation of the HCP crystal structure. Here ED, TD, and ND stands for extrusion direction, transverse direction, and normal direction, respectively.

boundaries. Here, different variants of tensile twinning would be preferentially operative owing to very low CRSS ~ 2–5 MPa. It is also obvious that the twinning fraction increased with an increase in strain and at the later stages of deformation, the contraction and double twinning can also operative which leads to crack in Mg alloys. However, one should be clear about the fracture to elongation under compression and then decided for the pre-strain level. For ZK based Mg alloys, the pre-strain level would be ~10% [23,24]. The loading up to such a high strain can induce <c+a> slip system in the specimen. Thirdly, if we loaded the same specimen in the same direction again, the twin growth mechanism has to occur. However, changing the loading direction leads to the de-twining phenomenon. It is obvious that the tensile twinning during in-plane compression provided the different twin variants, therefore some of the variants might be preferentially operative for twin growth and some of them might be advantageous for de-twinning during cross pre-compression. Moreover, it is anticipated that the fresh grains that were unfavorable for twinning owing to twin path dependencies during pre-compression may govern twin induced deformation and thereby further decreased the grain size. During the whole process, not only the grain size will be reduced but also the crystallographic orientations greatly change and hence altered the texture significantly. This change can be sum up in Fig. 1. However the size of the specimen has a big influence on the texture and twinning therefore the same size of the specimen i.e., the cubic specimen is most appropriate for the accurate changes in the crystallographic orientations. Most specifically, one can predict the obvious changes of the crystallographic orientations based on the initial compressive response of the same specimen so the compression up to a fixed strain on a big size specimen may influence the twinning and the texture. So, according to formula (Stress = Force/Area), the greater the area of the specimen the smaller the stress, and hence the smaller the strain. Thus, the predicted strain cannot be achieved and hence obvious changes in the crystallographic cannot also achieve.

Further, the tensile and compressive specimens of ASTM standard machined form the cross pre-compressed Mg alloys must exhibit isotropic mechanical behavior. In consequences of textural changes, the c-axis of the grains orientations changes to new orientations parallel and perpendicular to the normal direction of the sheet. Therefore the new orientations would provide different Schmid factors for the different slip activity in comparison to the extruded Mg alloy (Basal Sf~ 0 for strong basal texture for tension along ED). It is accepted that the most frequent slip mode is basal slip therefore, it is highly expected that the basal slip activity would enhance during deformation. Therefore, the synergetic effect of pre-induced <c+a> slip, enhanced <a> basal slip activity due to textural changes, grain refinement through twin boundaries, and interaction of twinning and dislocation slip during deformation can increase the YS, ultimate strength (both compressive and tension) and FE% of the alloys. Thus, the cost-effective cross pre-compression can be productive in terms of increasing the strength, ductility, and elimination of anisotropic mechanical behavior of Mg alloys.

This technical report was focused on an alluring practical cross pre-compression approach for the further development of high performance wrought Mg alloys. The Mg alloys can be cross pre-compressed up to engineering strain 7–10% along with different directions. This technique can produce profuse $\{10\bar{1}2\} < 10\bar{1}1 >$ extension twin activity and redistribution of the <c> axes orientations from parallel to the normal direction (c-axes//ND) to perpendicular to the normal direction (c-axis⊥ND). Before pre-compression, the dimension of the specimens must be the same, so that predictive results can be achieved. The twin induces grain refinement together with texture changes, pre-induced <c+a> and high activity of <a> basal slip owing to redistributed texture can further significantly increase the strength and exacerbation of the anisotropic behavior of Mg alloys. Therefore, cross pre-compression can be an alluring cost-effective approach for the further development of wrought Mg alloys.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This project is financially supported by the National Natural Science Foundation of China.(Grant No.51702015).

References

[1] A. Malik, Y. Wang, C. Huanwu, F. Nazeer, M.A. Khan, Dynamic mechanical behavior of magnesium alloys: a review, Int. J. Mater. Res. 110 (12) (2019) 1105–1115.

[2] A. Malik, W. Yangwei, C. Huanwu, F. Nazeer, M.A. Khan, W. Mingjun, Microstructural evolution of ultra-fine grained Mg-6.62Zn-0.6Zr alloy on the basis of adiabatic rise in temperature under dynamic loading, Vacuum 168 (2019) 108810.

[3] S. Paul, P. Ramasamy, M. Das, D. Mandal, O. Renk, M. Calin, J. Eckert, S. Bera, New Mg-Ca-Zn amorphous alloys: biocompatibility, wettability and mechanical properties, Materialia 12 (2020) 100799.

[4] D.O. Okanigbe, M.K. Ayomoh, O.M. Popoola, P.A. Popoola, V.S. Aigbodion, Oxidative roasting experimentation and optimum predictive model development for copper and iron recovery from a copper smelter dust, Results Eng 7 (2020) 100125.

[5] F. Nazeer, Z. Ma, L. Gao, S. Abrar, A. Malik, M.A. Khan, F. Wang, H. Li, Higher mechanical and thermal properties of Cu-rGO composites, Vacuum 180 (2020) 109584.

[6] E.Y. Salawu, O.O. Ajayi, A. Inegbenebor, S. Akinlabi, E. Akinlabi, Influence of pulverized palm kernel and egg shell additives on the hardness, coefficient of friction and microstructure of grey cast iron material for advance applications, Results Eng 3 (2019) 100025.

[7] S.A. Akintola, M. Oki, A.A. Aleem, A.A. Adediran, O.B. Akpor, O.M. Oluba, B.T. Ogunsemi, P.P. Ikubanni, Valorized chicken feather as corrosion inhibitor for mild steel in drilling mud, Results Eng 4 (2019) 100026.

[8] A.A. Adeleke, P.P. Ikubanni, T.A. Orhadahwe, J.O. Aweda, J.K. Odusote, O.O. Agboola, Microstructural assessment of AISI 1021 steel under rapid cyclic heat treatment process, Results Eng 4 (2019) 100044.

[9] R. Azzawi, N. Varughese, Flexural behavior of preflex sfrc-encased steel joist composite beams, Results Eng 7 (2020) 100122.

[10] T. Balarami Reddy, P. Karthik, M. Gopi Krishna, Mechanical behavior of Al–Cu binary alloy system/Cu particulates reinforced metal-metal composites, Results Eng 4 (2019) 100046.

[11] H.I. Akbar, E. Surojo, D. Ariawan, A.R. Prabowo, Experimental study of quenching agents on Al6061–Al2O3 composite: effects of quenching treatment to microstructure and hardness characteristics, Results Eng 6 (2020) 100105.

[12] A. Malik, W. Yangwei, C. Huanwu, M.A. Khan, F. Nazeer, A. Rui, B. Jiawei, W. Mingjun, Fracture behavior of twin induced ultra-fine grained ZK61 magnesium alloy under high strain rate compression, J. Mater. Res. Technol. 8 (4) (2019) 3475–3486.

[13] H. Huang, H. Miao, G. Yuan, C. Chen, H. Zhang, J. Pei, Z. Wang, Deformation behavior and texture randomization of Mg–Zn–Gd alloys reinforced with icosahedral quasicrystal, Int. J. Mater. Res. 108 (6) (2017) 455–464.

[14] H. Zhou, C. Chen, Y. Du, H. Gong, Experimental investigation and thermodynamic calculation of the Mg–Sr–Zr system, Int. J. Mater. Res. 107 (6) (2016) 534–543.

[15] M. Klein, P. Wittke, R. Hoppe, D. Letzig, F. Walther, Corrosion fatigue assessment of extruded magnesium alloys AZ31 and ME20, Materials Testing 60 (1) (2018) 15–21.

[16] E.A. Sterling Lee, C.W. Sinclair, The effect of precipitation on recrystallization in a Mg-Nd alloy, Materialia 10 (2020) 100643.

[17] D. Kumar, S. Goel, N.N. Gosvami, J. Jain, Towards an improved understanding of plasticity, friction and wear mechanisms in precipitate containing AZ91 Mg alloy, Materialia 10 (2020) 100640.

[18] W.C. Zhang, Y. Yu, X.N. Zhang, W.Z. Chen, E.D. Wang, Mechanical anisotropy improvement in ultrafine-grained ZK61 magnesium alloy rods fabricated by cyclic extrusion and compression, Mater. Sci. Eng., A 600 (2014) 181–187.

[19] L. Zhang, W. Chen, W. Zhang, W. Wang, E. Wang, Microstructure and mechanical properties of thin ZK61 magnesium alloy sheets by extrusion and multi–pass rolling with lowered temperature, J. Mater. Process. Technol. 237 (2016) 65–74.

[20] L. Li, Y. Wang, C. Zhang, T. Wang, H. Lv, W. Yu, Ultrafine-grained Mg–Zn–Yb–Zr alloy with simultaneously improved strength and ductility processed by axisymmetric hot extrusion, Vacuum 173 (2020) 109157.

[21] M. Wang, B.B. He, M.X. Huang, Strong and ductile Mg alloys developed by dislocation engineering, J. Mater. Sci. Technol. 35 (3) (2019) 394–395.

[22] A. Malik, Y. Wang, F. Nazeer, M.A. Khan, Effect of pre-compression on changes in texture and yielding behavior of ZK61 Mg alloy, Vacuum 172 (2020) 109039.

[23] A. Malik, Y. Wang, C. Huanwu, F. Nazeer, B. Ahmed, M.A. Khan, W. Mingjun, Constitutive analysis, twinning, recrystallization, and crack in fine-grained ZK61 Mg alloy during high strain rate compression over a wide range of temperatures, Mater. Sci. Eng., A 771 (2020) 138649.

[24] J. Li, Y. Wang, Impact of pre-straining on the hardness and anisotropic mechanical behavior of ZK61 Mg alloy, Vacuum 178 (2020) 109465.