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EFFECT OF Fe CONTENT ON THE MECHANICAL PROPERTIES AND THERMAL CONDUCTIVITY OF THE Al-RE ALLOYS

In this study, we investigated the effect of Fe addition (0, 0.25, 0.50 and 0.75 wt.%) on the microstructure, mechanical properties and electrical conductivity of as-cast and as-extruded Al-RE alloys. As the Fe element increased by 0 and 0.75wt.%, the phase fraction increased to 5.05, 5.76, 7.14 and 7.38 %. The increased intermetallic compound increased the driving force for recrystallization and grain refinement. The electrical conductivity of Al-1.0 wt.%RE alloy with Fe addition decreased to 60.29, 60.15, 59.58 and 59.13 %IACS. With an increase in the Fe content from 0 to 0.75 wt.% the ultimate tensile strength (UTS) of the alloy increased from 74.3 to 77.5 MPa. As the mechanical properties increase compared to the reduction of the electrical conductivity due to Fe element addition, it is considered to be suitable for fields requiring high electrical conductivity and strength.

Keywords: Aluminum, Extrusion, Rare Earth, Thermal conductivity, Mechanical property

1. Introduction

Recently, researches for improving heat dissipation characteristics of products have been actively conducted in accordance with the trend of high integration and high output of electrical and electronic devices. As the ICT industry is advanced, the demand for heat dissipation parts such as high-power LEDs is increasing due to the high integration and high output of electric and electronic products. Among them, aluminum alloys are inexpensive compared to copper and its usage is increasing because of its excellent conductivity [1,2]. However, the existing aluminum alloy has a problem that the surface treatment such as anodizing is impossible with the decrease in conductivity due to the high Si content. The addition of other elements to pure aluminum lowers the conductivity due to solute atoms, grain boundaries, dislocations and deposits. The most important effect on the reduction of electrical conductivity occurs in solute atoms [3].

Therefore, the Al-based immiscible systems such as Al-RE or Al-Fe are considered to be promising materials for high conductors because they have zero solubility in Al and have little effect on electrical conductivity [4-6]. In addition, uniform distribution of small intermetallic compounds throughout the alloy can greatly increase mechanical strength and thermal stability [7]. However, control is necessary because excessive amounts of immiscible element compounds can cause loss of electrical conductivity [3].

Al-RE alloys are stronger than pure aluminum, but still lack strength due to the large particles of intermetallic compounds. Since, demand for high strength aluminum alloy was significantly increased, it is necessary to characterize the effect of Fe and set the tolerable amount of Fe content in aluminum alloys [8]. There is a need to improve the mechanical properties of the alloy through grain refinement and breaking and redistribution of intermetallic compounds.

In this study, we investigated the effect of Fe addition on the microstructure, mechanical properties and electrical conductivity of as-cast and as-extruded Al-RE alloys.

2. Experimental

The alloys used in this study had the nominal composition of Al-1.0 wt.%RE-xFe alloys (x = 0, 0.25, 0.50 and 0.75 wt.%). The melt was held at 780°C for 20 min and then poured into a pre-heated steel mold (diameter = 75 mm, height = 250 mm) at 200°C. The cast alloys were machined into billets with a diameter of 70 mm and a height of 90 mm. The machined billets were homogenized at 550°C for 8 h. The billets were hot extruded into rod that were 12 mm in diameter with a reduction ratio of 38:1 at 500°C. In order to observe their microstructures, the specimens were polished with a diamond suspension of 3 μm and 1 μm,

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and then silica suspension was used for the fine polishing. The microstructures of the alloys were examined using a field emission scanning electron microscopy (FESEM) and electron backscatter diffraction (EBSD) system. The phase composition of the alloys was examined using an X-ray diffractometer (XRD) with Cu Kα radiation. The electric conductivities of the alloys were measured using the eddy current method at room temperature. The mechanical properties of the as-extruded Al alloy specimens were measured by universal testing machine with ASTM E8M standard. Tensile tests were carried out at an initial strain rate of 1.0×10^{-3} s^{-1}.

3. Results and discussion

Fig. 1(a)-(d) shows the SEM-BSE images of the as-cast Al-1.0 wt.%RE-xFe alloys (x = 0, 0.25, 0.5 and 0.75 wt.%). As shown in Figure 1, intermetallic compounds (with bright contrast) were distributed in the grain boundaries. The microstructure of Fe addition alloy comprised of Al and precipitates; the volume fraction of phases in the as-cast specimens, measured through an image analysis method, was approximately 94.95% and 5.05% for Al and 2-phase, respectively (Fig. 1(a)). As the Fe element increased by 0 and 0.75wt.%, the phase fraction increased to 5.05, 5.76, 7.14 and 7.38 %. The fraction of intermetallic compounds is thought to affect the electrical conductivity and mechanical properties of Al-RE alloys.

Fig. 2(a)-(d) shows the SEM-BSE images of the as-extruded Al-1.0 wt.%RE-xFe alloys (x = 0, 0.25, 0.5 and 0.75 wt.%). As can be observed from Fig. 2, the intermetallic compounds distributed in the grain boundaries of the casting aligned in a direction parallel to the extrusion direction during the hot extrusion process. They also fragmented into slightly smaller particles by severe deformation during the extrusion. The intermetallic

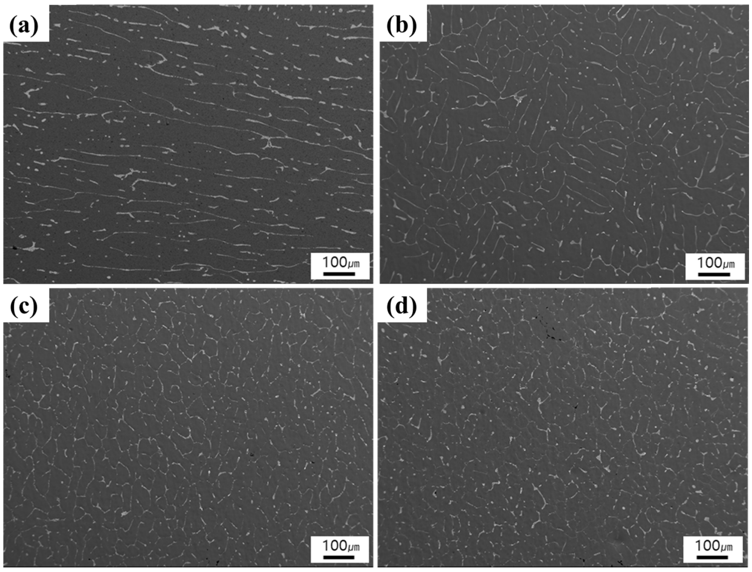

Fig. 1. SEM-BSE images of the as-cast Al-1.0wt.%RE-xFe alloys (x = (a) 0, (b) 0.25, (c) 0.50, (d) 0.75wt.%)

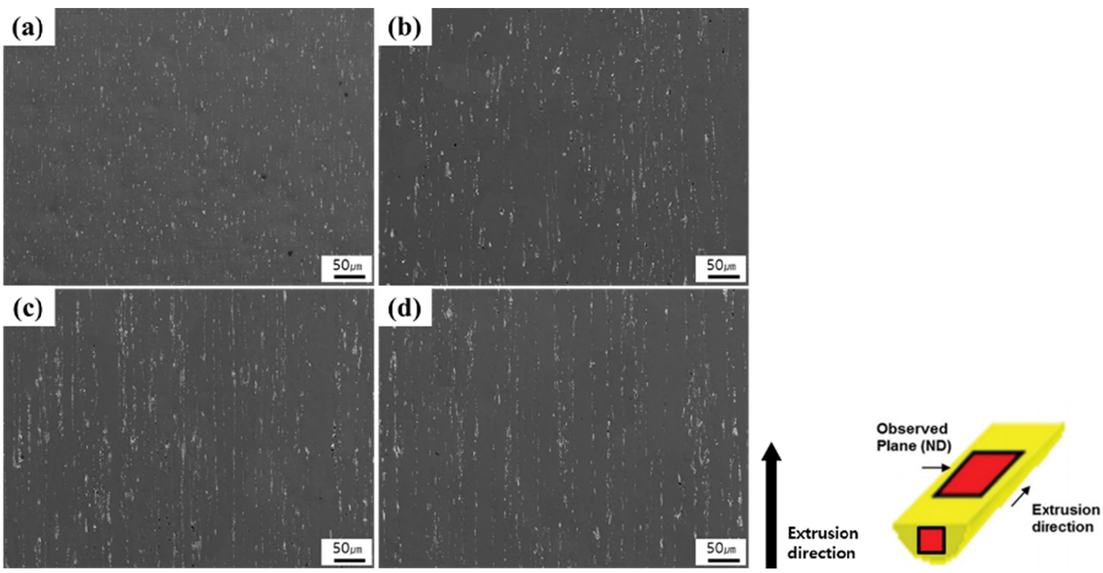

Fig. 2. SEM-BSE images of the as-extruded Al-1.0wt.%RE-xFe alloys (x = (a) 0, (b) 0.25, (c) 0.50, (d) 0.75wt.%)

compound was expected to promote dynamic recrystallization during extrusion.

Fig. 3 shows the XRD patterns of the alloy extruded Al-1.0wt.%RE-xFe alloys (x = 0, 0.25, 0.5 and 0.75wt.%). The XRD pattern showed a strong peak on the Al phase. Peaks were also observed in the $Al_{11}RE_3$ phases. The XRD results were consistent with the results reported in preceding literature. The $Al_{11}RE_3$ phase is more stable at temperatures below 1000 K as opposed to the Al4RE isotope, which has been studied widely [9]. Therefore, it can be concluded that while the α-Al and $Al_{11}RE_3$ phases are stably present in the Al-rich binary system at low temperatures, the Al_4RE phase cannot be observed in this experiment [10]. However, no Fe-containing phase was detected.

The grain characteristics of the as-extruded Al-1.0wt.%-RE-xFe alloys were investigated by carrying out their EBSD

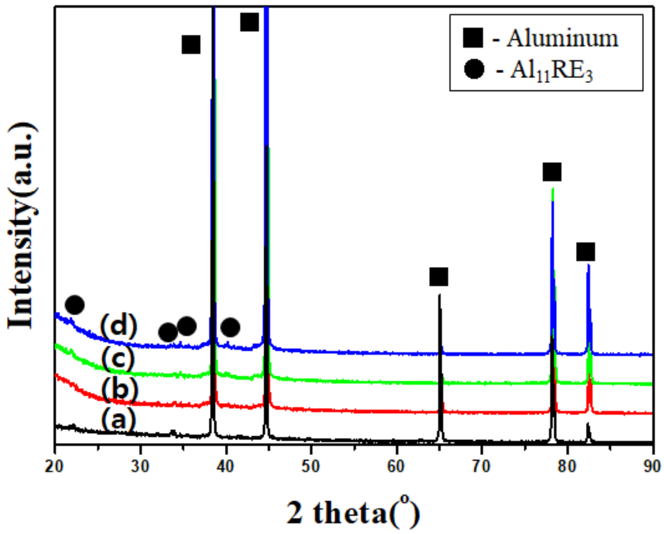

Fig. 3. XRD patterns of the as-extruded Al-1.0wt.%RE-xFe alloys (x = (a) 0, (b) 0.25, (c) 0.50, (d) 0.75wt.%)

analysis in a direction parallel to the extrusion direction, as shown in Fig. 4. The EBSD map and grain rotation angle map were taken parallel to the extrusion direction. When the Fe addition amount was increased to 0, 0.25, 0.50 and 0.75wt.%, it decreased to 739.8, 279.3, 225.9 and 163.5 μm. The increased Fe-phase increased the driving force for recrystallization and grain refinement. The Al-1.0RE alloy without Fe showed recrystallized and non-recrystallized grains, and non-recrystallized grains were stretched in band shape along the extrusion direction, as shown in Fig. 4(a). The recrystallized grains were equiaxed morphology and the grain size was smaller than that of the non-recrystallized grains. In Fig. 4, the low-angle boundaries (LGBs) (misorientation of 2-15) and high-angle boundaries (HGBs) (misorientation larger than 15) are shown in red, green, and blue regions, respectively. The non-recrystallized graion regions showed LGBs and recrystallized grain regions were mainly HGB. The Al-1RE and 0.25, 0.50 wt.% Fe-containing alloys showed non-recrystallized grains, while the 0.75 wt.% Fe-containing alloys were mostly composed of dynamic recrystallized (DRX) grains. An increase in the Fe content resulted in the occurrence of grain refinement because of the occurrence of DRX due to the severe plastic deformation during the extrusion. It has been reported that solute atoms can affect the DRX process not only by decreasing the stacking fault energy (SFE) but also by hindering the dislocation rearrangement [11]. Thus, it is believed that solute Fe atoms enhance the DRX nucleation by increasing the number of nucleation sites and promote the rotation and growth of sub-grains by reducing the SFE.

Fig. 5 shows the changes in the electrical conductivity and thermal conductivity according to the casting and extrusion process. The electrical conductivity of the cast material showed low electrical conductivity due to porosity and fine casting defects. As the Fe content increased from 0 to 0.75wt.%, the electrical conductivity of the extruded Al-1.0 wt.%RE alloy decreased by

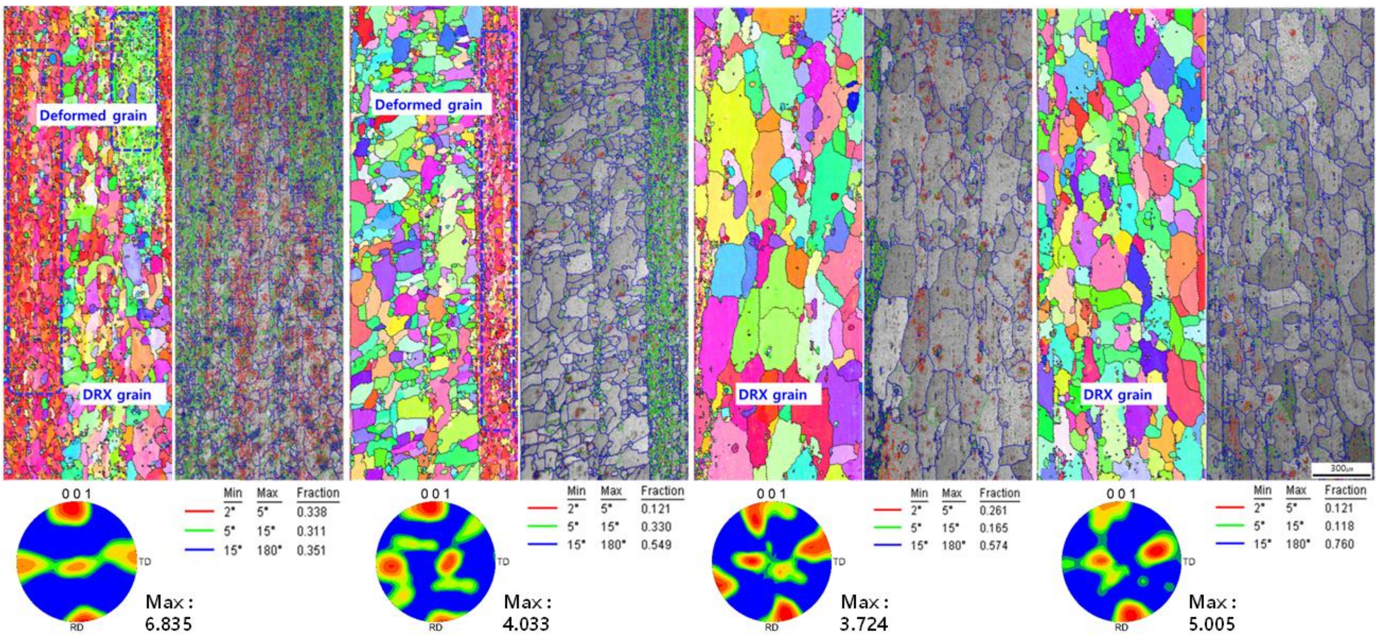

Fig. 4. IPF maps, grain orientation images and pole figures of the as-extruded Al-1.0wt.%RE-xFe alloys

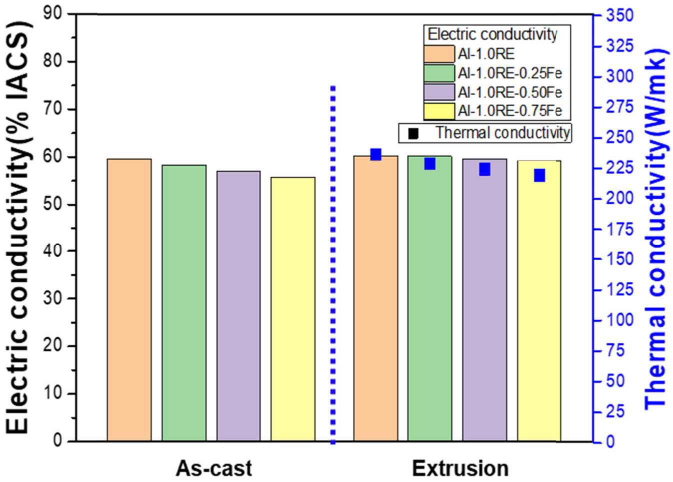

Fig. 5. Variations in the electric conductivity, and thermal conductivity of the as-cast and as-extruded alloys with the Fe conten

60.29, 60.15, 59.58 and 59.13 %IACS (International annealed copper standard). It is considered that the effect of increasing the total phase fraction with increasing Fe element. The thermal conductivity of the alloys decreased with an increase in the Fe content. The alloys with 0, 0.25, 0.50 and 0.75wt.% Fe showed a thermal conductivity of 236, 55, 228,62, 223.74 and 219.04 W/mK, respectively.

Fe atoms formed a solid solution in the a-Al matrix, which affected the electrical and thermal conductivity of the alloy. Alloying elements affect the electrical and thermal conductivity of Al alloys in several aspects. Alloying elements dissolve in the α-Al matrix and affect the mean free paths of electrons and phonons due to lattice distortion caused by the solute atoms. When the amount of the alloying element exceeds the solid solubility of Al, an intermetallic compound having a different form is formed [12]. The thermal conductivity of an alloy is sensitive to microstructure, and can affect the thermal conductivity of different degrees of lattice distortion due to different solute atoms [13]. Therefore, as the Fe content increases, severe distortion of the α-Al matrix occurs, thereby decreasing the electron mean free path, and the electrical conductivity and thermal conductivity of the alloy.

Fig. 6 shows tensile properties of the as-extruded Al-1.0wt.%RE-xFe (x = 0, 0.25, 0.50 and 0.75wt.%) alloys at room temperature. The yield strength (YS) and ultimate tensile strength (UTS) of the as-extruded Al-1.0RE alloy without Fe were 53.3 and 74.3 MPa, respectively. With increasing Fe addition from 0.25, 0.50 and 0.75wt.%, ultimate tensile strength was increased from 71.3, 75.2 and 77.5 MPa. The elongation with Fe addition amount increased from 44.4 to 46.3 % and then decreased to 39.5%. Fe addition to Al-1.0 wt.%RE alloy contributed to the improvement of tensile strength. It can be seen that the strength are improved due to the grain refinement and precipitation strengthening effect due to Fe element addition. The addition of Fe significantly influenced the strength improvement, the thermal conductivity, and the electrical conductivity reduction. Generally, the effect of Fe-rich phases on the mechanical properties of aluminum alloys depends on their type, size and amount in the microstructure. Fe-rich intermetallic significantly affect the mechanical properties of the alloy castings. The higher the iron concentrations in the alloy, the more significantly the ductility reduces [14].

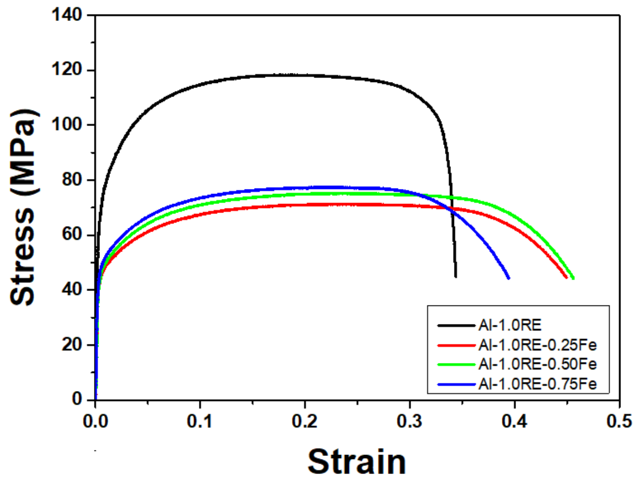

Fig. 6. Tensile stress-strain curves of the as-extruded Al-1.0wt.%RE-xFe alloys

4. Conclusions

In this study, the effects of Fe addition on the microstructure and mechanical properties of Al-1.0 wt.%RE alloys were investigated. In the case of the Al-1.0 wt.%RE alloy, the addition of Fe resulted in grain refinement because of the dynamic recrystallized (DRX) process caused by the Fe solute atoms during the extrusion. As the Fe content increased from 0 to 0.75 wt.%, the average grain size of the extruded Al alloy decreased by 739.8 to 163.5 μm and the high-angle grain boundaries (HGBs) fraction increased from 35 to 76 %. The increased intermetallic compound increased the driving force for recrystallization and grain refinement. The electrical conductivity of Al-1.0 wt.%RE alloy with Fe addition decreased to 60.29, 60.15, 59.58 and 59.13 %IACS. With an increase in the Fe content from 0 to 0.75 wt.% the ultimate tensile strength (UTS) of the alloy increased from 74.3 to 77.5 MPa and the strain decreased from 44.4 to 39.5 %. This improvement in the strength of the alloys was caused by the grain refinement and solid solution strengthening effects of the Fe solute atoms. As the mechanical properties increase compared to the reduction of the electrical conductivity due to Fe element addition, it is considered to be suitable for fields requiring high electrical conductivity and strength.

Acknowledgments

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REFERENCES

[1] B. Ma, Y. Ahn, J. Kim, S. Choi, K. Lee, Thermal properties and lifetime comparison of various ceramic-package light-emitting diodes. Electronic Materials Letters **9** (4), 541-544 (2013).

[2] J.H. Son, Y.H. Song, B.J. Kim, J.L. Lee, Effect of reflective P-type ohmic contact on thermal reliability of vertical InGaN/GaN LEDs. Electronic Materials Letters **10** (6), 1171-1174 (2014).

[3] A.E. Medvedev, M.Y. Murashkin, N.A .Enikeev, R.Z. Valiev, P.D. Hodgson, R. Lapovok, Enhancement of mechanical and electrical properties of Al-RE alloys by optimizing rare-earth concentration and thermo-mechanical treatment. Journal of Alloys and Compounds **745**, 696-704 (2018).

[4] D.H. Kim, B. Cantor, Structure and decomposition behaviour of rapidly solidified Al-Fe alloys. Journal of materials science **29** (11), 2884-2892 (1994).

[5] A.A. Mogucheva, D.V. Zyabkin, R.O. Kaibyshev, Effect of annealing on the structure and properties of aluminum alloy Al-8% MM. Metal Science and Heat Treatment **53** (9-10), 450-454 (2012).

[6] S.S. Nayak, M. Wollgarten, J. Banhart, S.K. Pabi, B.S. Murty, Nanocomposites and an extremely hard nanocrystalline intermetallic of Al-Fe alloys prepared by mechanical alloying. Materials Science and Engineering: A **527** (9), 2370-2378 (2010).

[7] E.V. Bobruk, M.Y. Murashkin, V.U. Kazykhanov, R.Z. Valiev, Aging behavior and properties of ultrafine-grained aluminum alloys of Al-Mg-Si system. Rev. Adv. Mater. Sci. **31**, 109-115 (2012).

[8] H. Lu, Z. Hou, M. Ma, G. Lu, Effect of Fe-content on the mechanical properties of recycled Al alloys during hot compression. Metals **7** (7), 262 (2017).

[9] Q. Yang, X. Liu, F. Bu, F. Meng, T. Zheng, D. Zhang, J. Meng, First-principles phase stability and elastic properties of Al-La binary system intermetallic compounds. Intermetallics **60**, 92-97 (2015).

[10] C.A.O. Zujun, K.O.N.G. Gang, C.H.E. Chunshan, W.A.N.G. Yanqi, P.E.N.G. Haotang, Experimental investigation of eutectic point in Al-rich Al-La, Al-Ce, Al-Pr and Al-Nd systems. Journal of Rare Earths **35** (10), 1022-1028 (2017).

[11] J. Zou, J. Chen, H. Yan, W. Xia, B. Su, Y. Lei, Q. Wu, Effects of Sn addition on dynamic recrystallization of Mg-5Zn-1Mn alloy during high strain rate deformation. Materials Science and Engineering: A **735**, 49-60 (2018).

[12] L. Zhong, J. Peng, S. Sun, Y. Wang, Y. Lu, F. Pan, Microstructure and thermal conductivity of cast and as-extruded Mg-Mn alloys. Material Science and Technology **33** (11), 92-97 (2017).

[13] T. Ying, H. Chi, M. Zheng, Z. Li, C. Uher, Low temperature electrical resistivity and thermal conductivity of binary magnesium alloys. Acta Materialia **80**, 288-295 (2014).

[14] S. Ji, W. Yang, F. Gao, D. Watson, Z. Fan, Effect of iron on the microstructure and mechanical property of Al-Mg-Si-Mn and Al-Mg-Si diecast alloys. Materials Science and Engineering: A **564**, 130-139 (2013).