Challenge in magnesium microforming

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Abstract. Microforming is a method of manufacturing near-net shape micro parts by plastic deformation. This method has attracted much attention and is potentially adopted to manufacture various micro parts due to its distinct advantages, such as good strength of the deformed parts, high production rate, less scraps, and low cost. Among the materials studied in microforming research, copper is the most studied material, followed by aluminum and steel. Recently, magnesium has become an interesting research topic since the trend of magnesium application has emerged in electronics and medical fields. However, magnesium has low formability at room temperature that makes magnesium microforming a challenge. Hence, this paper discusses an overview about recent development in magnesium microforming and the challenges in controlling the size effect and formability of magnesium by elevated temperature and grain refinement.

Keywords: microforming, magnesium, elevated temperature, grain refinement

1. Introduction
A global trend towards progressive miniaturization products such as electronic devices or medical equipment has given an emphasis on the development of micromanufacturing technologies. Microforming is a promising solution, although machining process is currently the main fabrication technique. Microforming is a process of manufacturing parts in the submillimeter range by plastic deformation [1]. It can produce near net shape microparts with high mechanical properties, high productivity, and low production cost by minimizing material waste.

One of the main concerns with microforming systems is material parameters [2]. When the dimension of material is scaled down while the microstructure is fixed, then the ratio of dimension and microstructure will change, which is known as size effect. The flow stress, forming limit, fracture, and surface roughness are strongly influenced by size effect [3]. The size effect causes scatter in the process and product. This condition is undesirable and needs to be controlled.

Magnesium application in microforming is still limited and needs more research to resolve problems of the size effect of microforming and the low formability of magnesium. This paper discusses the challenges in magnesium microforming with a focus on appropriate strategies to control size effect in microforming and to improve formability of magnesium by elevated temperature process and grain refinement.

2. Material Factor in Microforming
The parameters of macroforming cannot be adopted directly to microforming due to the size effect that has to be considered [4]. The size effect causes material behavior or properties at the microscale to be different from that at the macroscale level. When the dimension is scaled down to micro scale range, it generates only a few numbers of grains in the forming area. Hence, deformation will be influenced by the orientation of the individual grains. Moreover, decreasing the volume can reduce defects and increasing the ratio of surface to volume. The external force that acts on the part, such as van der Waals,
gravitation, and surface tension, can be neglected in macroforming because they are too small. However, the force becomes relatively large in the microforming process [5]. They will result in scattering or instability of deformation behavior in the microforming process [2, 6].

Scattering can be influenced by the ratio of the specimen size to grain size ($\lambda$). Diehl et al. observed that the scatter of coarse-grained material is larger than fine-grained material. As the grain size is refined, the scatter becomes less significant. Moreover, the effect of individual grain on the deformation and inhomogeneous microstructure decreases [7]. The influence of size effect on material behavior in microforming process is illustrated in figure 1.

![Figure 1. Size effect parameter in microforming.](image)

2.1 Flow stress
Size reduction causes an increase in the free surface of the material and a decrease in flow stress. The flow stress depends on the grain size, crystallographic orientation, and dislocation density of a few grains during deformation [8]. Due to the inhomogeneity condition of the grains located in the deformation region, the scatter of deformation can be seen under homogeneous loading conditions [6].

Chan et al. investigated that flow stress decreased along with the reduction of sheet metal thickness ($t$) or with the increase of the grain size ($d$). The increase of grain size lessens grain boundary strengthening effect and interfacial friction that assist the deformation [9, 10]. Ma et al. proposed that the scatter of flow stress increases with the decrease of $t/d$ ratio [11]. The decrease of $t/d$ will result in the number of grains in the deformation region become lesser and will affect the anisotropy that leads to scattering. The considerable scattering >5% will appear when there less than 50 grains inside the deformation region as investigated by Justinger et al. [12].

2.2 Forming limit
Xu et al. found that the size effect and forming limit decrease with $t/d$ as the forming limit curve shifts down. If the number of grains is one or two grains over the thickness of the material, the strain localization tends to occur at the beginning of the deformation and the scatter of forming limit gets much worse [13, 14]. The microscale forming limit curve ($\mu$-FLC) of sheet metal could be influenced by the size effect. $\mu$-FLCs move down as the grain size increasing, which conforms to the study conducted by Xu et al. [15].

2.3 Ultimate shearing strength
In the micro blanking process, the size effect is not only influenced by the thickness and grain size but also clearance ($c$). Xu et al. revealed that the blanking force and ultimate shearing strength reduce as the relative blanking clearance ($c/t$) increasing until reaching the minimum shear strength. Then, the shear strength increases with a further increase in relative blanking clearance ($c/t$). Meanwhile, the relation of size effect with grain size ($c/d$) has also been investigated. When $c/d$ is less than 1, the ultimate shearing strength decreases with the increase of $c/d$. However, when $c/d$ is equal to 1, the ultimate shearing strength achieves a minimum value, and then the ultimate shearing strength increases with the increase of $c/d$. Furthermore, a strong variation of maximum blanking force and the curve profile have been found in coarse grain material. It shows that the scatter is more dominant in coarse grain [16].
2.4 Fracture

In microforming, the ductile fracture is a challenging research topic that is closely linked to manufacturing reliability and quality [13]. Fracture is one of the defects that is caused by the tensile stress exceeding the strength limit of the material. To avoid fracture, controlling the amount and uniformity of deformation in each forming step is required. A fracture could be initiated by free surface roughening or nucleation and growth of voids inside the material [15]. Fu et al. investigated the influence of changing specimen dimension and grain size on the deformation and fracture behaviors in microscale plastic deformation. The deformation mechanism is mainly caused by grain boundary sliding and grain rotation of the surface grains [17]. The number of microvoids on the fracture surface decreases with t/d [14]. Fang et al. explored fracture and deformation behavior. When t/d is less than 1, the materials tend to have a brittle fracture, while when t/d is greater than 1, materials tend to have ductile fracture [18]. Hence, the mode of fracture is significantly determined by the thickness to grain size ratio. Further investigation of ductile fracture was accomplished by Meng et al. with the addition of surface roughness. The surface roughening of deformed specimens increases with the decrease of t/d ratio due to the lower constraint of the surface grains [19]. Wang et al. proposed that the fracture strain and the number of microvoids on the fracture surface decrease with the proportion of t/d [20].

2.5 Surface roughness

The roughening effect can be seen in materials with a few available slip systems such as hexagonal close-packed structure. A rough surface can impact strain concentration, forming limit, interface friction between tooling-workpiece, and mechanical properties of the formed microparts. While the specimen size remains constant, the side surface becomes rougher with a decrease of λ [21]. The scraggly topography exhibited in the specimen surface is due to the inhomogeneous deformation of surface grains [22]. The size effect decreases with an increase in contact pressure between the workpiece and dies [23].

![Figure 2. Size effect with variations of d/b [24].](image)

In the coining process, the size effect of microforming is related to the dimension of dies as depicted in figure 2. For the grain size (d) to groove width (b) ratio larger than 0.5, the microforming performance increases correspondingly. In contrast, the microforming performance also increases with the decrease of d/b, when d/b is less than 0.5. The deformation occurs as a homogeneous polycrystalline material when the grain size is less than the groove width. However, the single grain deformation occurs when the grain size is equal to or larger than the groove width [24].

3. Magnesium Microforming

Magnesium has low density (1.8 g/cm3) and its strength-to-weight ratio is higher than that of aluminum (Al), titanium (Ti), and steel [25]. Magnesium is preferable for the automotive and aerospace industry for reducing the weight of structural components. In the medical field, magnesium application is required due to its biocompatibility with the human body. However, magnesium alloy applications are restricted since magnesium has poor room temperature formability [26]. Many manufacturing applications of magnesium are performed by machining. Since the forming process is a promising manufacturing technology to increase production rate and reduce material waste, forming magnesium is a challenge to be solved.

At room temperature, magnesium is hard to form because of the low deformation modes of its hexagonal closed packed (HCP) structure and a strong texture as a result of previous thermomechanical
processes. Actually, magnesium has the basal, prismatic, and pyramidal slip systems and twinning as a secondary deformation mechanism. At room temperature, only basal slip system and tensile twinning can be operated due to the low critical resolved shear stress (CRSS). The non-basal slip systems have high values of CRSS which is not active. Consequently, the number of available slip systems is insufficient to accomplish the uniform deformation of the material [27, 28]. Additionally, the basal slip systems do not enable strain along the c-axis that is parallel to the loading direction. Hence, the activation of non-basal slip systems and the weakening of strong basal texture from the preliminary process are needed to improve formability.

Figure 3. Material studies in the microforming research [29].

Research on magnesium microforming is still limited compared to research on other materials, such as aluminum, copper, and steel as depicted in figure 3. The small number of related research is still incomprehensive and has not covered different kinds of process in microforming and for certain magnesium alloys as shown in Table 1. Consequently, the parameters and behavior of magnesium microforming are difficult to establish.

Table 1. Magnesium Microforming Process.

| Process         | Material       | Remarks                                      | References |
|-----------------|----------------|----------------------------------------------|------------|
| Micro compression | AZ31           | Ductility increase 80% at 200°C. Forming load reduces from 400 kg to 100 kg at 400°C. | [30]       |
| Micro forging    | AZ91           | Formability increase by HRDSR (grain size 0.5-0.8 µm) at 220-300°C. | [31], [32] |
| Micro punching   | AZ31, pure Mg  | Simultaneously heated and formed using an electrical resistance heater at 200-250°C. | [33], [34] |
| Micro extrusion  | AZ31, AZ80     | A similar tendency in the relation between grain, dimension, and scatter of the deformation load to the established rules of the size effect for other metallic materials. | [35], [36], [37] |
Micro embossing  
Mg-Li  
The 50-200 µm micro-array [38] channels were affected by temperatures and grain size. The ultrafine-grained resulted in smooth and good filling quality.

Micro deep drawing  
Mg-Li  
The drawing force reduces 14.14% [39] and the surface roughness reduces 18.18% by using the oil and nano-particle lubricants.

4. Recent Development of Magnesium Microforming
The challenges in magnesium microforming, such as controlling the size effect and the poor formability of magnesium, need to be resolved. The research trend on magnesium microforming mainly focuses on the elevated temperature and grained refinement approach to improve formability, homogenizing, and stability process. The second approach, namely grain refinement, is an alternative approach to bring the process to a low temperature. The following section describes some techniques in both elevated temperature and grained refinement that are recently developed.

4.1 Elevated Temperature Process
Microforming is preferably applied at room temperature due to its simplicity and fast process, low corrosion rate, better surface quality, and lower cost. However, investigations on microforming with several materials indicate the homogenizing effect in microforming at elevated temperature, which is appropriate to control the size effects and to reduce scattering [40]. Moreover, elevated temperature increases the forming limits of deformation [41].

In magnesium macroforming, the process with elevated temperature is usually performed to enhance the formability by thermal activation of non-basal slip. The activation of basal and non-basal slip system can lead to the dynamic recrystallization (DRX) process by which improving formability [42]. The appropriate forming temperature for magnesium is above room temperature but below the recrystallization temperature. It is about 0.35 until 0.55 of the melting point or 200-300°C that is known as warm temperature [43]. Warm temperature is the solution to a moderate process variable, avoid grain growth, and result in greater part dimension accuracy with better surface finishing [44].

![Figure 4. Heating methods (a) laser heating [45] (b) resistance heating [33].](image)

Flow stress and formability of the magnesium alloy AZ31B as a function of temperature and strain rate was studied by Arentoft et al. The increasing temperature and reducing strain rate can enhance the
ductility of AZ31B up to more than 80% in temperature above 200°C. Heating workpieces reduces forming load from greater than 400 kg at room temperature to less than 100 kg at 400°C [30].

Generally, in the forming process, the workpiece is heated before inserted into the die. However, because in microforming the heat capacity of the workpiece is lower than cooling by environment, the heating source should be close to the workpiece and heating the die is proposed. A small heater is suggested to achieve an easy and flexible thermal system [30]. The heating methods that are commonly used in the elevated temperature process are laser heating and resistance heating as illustrated in figure 4. Matsuda proposed a method of microforming AZ31 magnesium alloys at temperature 200-250°C in which a workpiece is heated and formed simultaneously using an electrical resistance heater. The temperature of the workpiece rises by direct heat transfer from the mold. A higher tool temperature and forming speed is required to form high-quality products [33]. Further research was conducted by Indhiarto et al. by developing a low-temperature microforming process of AZ31B by high-density energy. The research mentioned that pulse frequency is regulated by pulse width and peak current [46].

The flow stress behavior as in macro forming and scattering is reduced by increasing the temperature. At higher temperatures, the activation mechanism of dislocation motion can deform unfavorable oriented grains, which is difficult at room temperature [47].

4.2 Grain Refinement

Grain refinement is an alternative approach for a low-temperature process, which can increase the mechanical properties of the material and superplastic forming ability at elevated temperatures [48]. Additionally, grain refinement has the benefits to reduce size effect and to improve formability [31, 49]. Fine-grained material produces more uniform flow and hardness distribution than the coarse grain material. The coarse grain will induce inhomogeneous deformation because when only a small number of grains is in the deformation area, the anisotropy grain properties become significant. A large number of slips pass through the grain boundary to achieve the strain continuity, which results in the blurred coarse grain boundary.

Kim et.al investigated the micro forging of magnesium alloy AZ91 with V-grooved dies. The AZ91 was refined by differential speed rolling (HRDSR). The fine grain AZ91 showed outstanding superplasticity and formability at temperatures 220-300°C. However, at 300°C, formability decreases due to grain growth. The experiment also revealed that the die filling is affected by the distance from the center of the die. The transition from superplastic to non-superplastic flow was proposed as a parameter, besides grain size, which influences the formability [31, 32].

Zhang at al. studied size effects on mechanical properties of hot extruded AZ31B magnesium alloy. The change in failure mode from a more ductile to a more brittle mechanism is influenced by the orientation of extrusion direction and thickness. The ductile fracture was shown in extrusion direction while mixed brittle fracture was observed at 45° angle or transverse direction. Additionally, the yield strength and the ultimate tensile strength increase with the decrease of the thickness for extrusion direction but the opposite effect was found at 45° direction or transverse direction [50].

Su et al. investigated micro embossing process of ultrafine-grained LZ91 Mg-Li to produce micro-array channels widths ranging from 50 µm to 200 µm. The channels were affected by temperatures and grain size. The ultrafine-grained resulted in smooth and good filling quality, but coarse grain resulted in uneven and wrinkled filling [38].

An experiment on isothermal micro-backward extrusion of coarse-grained as-cast AZ31 was done by Khandani for the fabrication of microtubes. The area around the punch radius had the highest density of shear bands and dynamically recrystallized grains were noticed. A similar tendency in the relation between grain, dimension, and scatter of the deformation load follows the established rules of the size effect for other metallic materials. In plastic deformation, an enormous scatter of deformation force will be formed when the grain size and the dimension of the sample are in the same order of magnitude. It is confirmed that the size, boundary, and distribution of grains influence the micro extrusion process [36]. Investigation of grain size effect and material behavior in micro extrusion was also carried out for AZ80. Forming force increases when the grain size is reduced due to the presence of more number of smaller grains that resist dislocation and cause strain hardening [37].
Kamali et al. studied the effect of applying nano-particle lubricant in microforming of Mg-Li alloy. The drawing force was reduced by 14.14% and the surface roughness up to 18.18% by using the oil and nano-particle lubricants [39].

Thermal activation and grain refinement have the probability to reduce inhomogeneous deformation and to improve deformed quality [51]. Microformability is considerably affected by grain size, dimension of dies, and temperature. When the temperature increases, the plastic deformation resistance and size effect also decrease. However, undesirable grain growth occurs above a certain temperature. Hence, to solve this problem, the method to increase material temperature should be carefully considered.

An effective grain refinement process of magnesium was achieved by severe plastic deformation (SPD) process. SPD is a metal deformation under high hydrostatic pressure to apply a very large strain on a bulk metal without any considerable change in the specimen’s dimensions [52].

Equal Channel Angular Pressing (ECAP) is a technique in SPD that produces an extremely fine grain structure of bulk material. Grained refinement microstructures depend on route, temperature, and number of passes during the ECAP process [19]. Supriadi et al. applied the ECAP process to refine the grain size of magnesium to fabricate mini-plate magnesium through micro punching process [34]. In addition, Biswas found super formable polycrystalline pure magnesium at room temperature that had been refined by Equal channel angular extrusion (ECAE) at a temperature below 80°C. The fine grain leads to enhancement of grain boundary sliding that facilitates further deformation [53].

Another technique to refine the magnesium is High Pressure Torsion (HPT). HPT has been conducted in AZ31 at room temperature with high pressure of 6.0 GPa. The grain size was reduced from ~35 µm to ~110 nm after ten turns [54]. The same parameter used in the HPT process of LZ91 Mg-Li alloy resulted in significant grain refinement from 30 nm to ~230 nm [55]. HPT technique resulted in small coin-shaped samples with 10–15 mm in diameter and 1 mm in thickness [56].

One of the best SPD methods to perform on the sheets is ECAR process. ECAR is a continuous severe plastic deformation process that combines ECAP and rolling processes result in large and thin sheets. Significant grain refinement process of AZ31 occurred with ECAR. After eight passes of process, the grain size was refined from 21 to 3.9 µm [57, 58].

5. Conclusion
Magnesium microforming has a good prospect to be developed because of many distinct advantages. However, the dimension is scaled down to micro part, which resulted in the occurrence of size effect and scattering to the microforming process and the product. Numerous studies have been done to investigate the size effect in microforming, but studies on magnesium microforming are limited in number. Furthermore, magnesium microforming has encountered a problem of poor formability of magnesium, especially at room temperature. In this regard, noticeable developments have been made in processing on elevated temperature and improvement of microstructure by grain refinement.

A moderate rise of process temperature can bring considerable reduction to the scattering that occurred in the micro-forming process of magnesium, hence it can improve the process stability and reliability. The elevated temperature process is an alternative solution to improve the homogenization of material flow and the unsymmetrical forming zone of the specimen. However, temperature control is needed to avoid grain growth at elevated temperature.

The grain refinement is an alternative approach for low temperature processes. This method can improve the formability of magnesium by grain boundary sliding and reduces the influence of size effect. An appropriate grain refinement technique is also important to avoid strong texture. Strong basal texture produces anisotropy and reduces formability since the material cannot accommodate strain along the c-axis. Finally, some progress has been made in magnesium microforming at low temperature. Since there has been only a limited amount of research in magnesium microforming, further research is still needed and becomes a chance to make comprehensive and optimized process parameters in different kinds of process methods of magnesium microforming.
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