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Abstract

Effects of various lubrication conditions on macroscale deep drawing have been investigated extensively while in microscale due to the open and closed lubrication pocket theory and friction coefficient escalation, proper lubricant concern becomes severe. Microforming is used to produce lighter and more energy-effective products accordingly; in this study, magnesium-lithium (Mg-Li) alloy is chosen to form a superior micro-cup due to its ultralight weight with outstanding ductility. Mg-Li is a new material in microscale; consequently, to study the mechanical properties, a heat treatment process is performed. The dry and oil lubrication conditions are chosen as benchmarks to investigate effects of TiO₂ oil-based nano-additive lubricant. Finite element (FE) modelling has been conducted and the simulated results are agreed well with the experimental results where the drawing force is significantly affected by the nano-particle. The formed cup quality regarding the surface roughness has been evaluated extensively by consideration of various parameters and the quality improvement is substantial.

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Abstract

Effects of various lubrication conditions on macroscale deep drawing have been investigated extensively while in microscale due to the open and closed lubrication pocket theory and friction coefficient escalation, proper lubricants concern becomes severe. Microforming is to produce lighter and more energy effective products accordingly, in this study, Magnesium-Lithium (Mg-Li) alloy is chosen to superior formed micro-cup due to its ultralight weight with outstanding ductility. Mg-Li is a new material in microscale consequently, to study the mechanical properties, heat treatment process is performed. The dry and oil lubrication conditions are chosen as benchmarks to investigate effects of TiO₂ oil-based nano-additive lubricant. Finite Element (FE) modelling has been conducted and the simulated results are agreed well with the experimental results where the drawing force is significantly affected by the nano-particle. The formed cup quality regarding the surface roughness has been evaluated extensively by consideration of various parameters and the quality improvement is substantial.

Keywords Micro deep drawing, Nano-particle lubrication, Friction size effects, FE simulation, Mg-Li alloy

1. Introduction

Aiming to reduce pollution, volume and cost besides producing multifunctional devices among medical, automotive and aerospace sectors have caused the miniaturisation trend increase considerably recently. Subsequently the need is led to develop wide range of micro-manufacturing. Furthermore, microforming as a micromanufacturing technology has captured a vast attention due to its benefits, including cost effective bulk production with a high accuracy, and capability of forming comprehensive diversity of materials [1,2]. Nevertheless, in comparison with LIGA (Lithography, Electroplating and Moulding) and Silicon-based micromanufacturing technologies which are relatively well-developed for Micro-Electro-Mechanical System (MEMS), microforming is a nascent promising technology [3,4]. To develop microforming processes, several issues regarding size effects are needed to be addressed. Scaled-down sample behaves differently in microforming process in terms of impact factors such as surface to volume ratio, flowability and surface characteristics in which, some of neglectable parameters play notable role in microscale in contrast with macroscale [5-

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7]. Thus, surface roughness in microforming is a part of sample geometry while in macroscale merely it is surface characteristic [8]. In addition to the conventional models, including Hall-Petch model, inclusive models such as the modified surface layer and open and close lubricant pockets models have been proposed to explain flow stress reduction and surface characteristics in microscale [9-11]. Yet, the mentioned and modified models are not capable of clarifying size effects expansively. Based on the open and close lubricant pockets, friction coefficient increases by decrease of specimen size, due to the increase of open to close lubricant pockets fraction consequently, commonly used lubricants in macroscale are unable to improve tribological characteristics in microscale [12,13] and lubricants overflow considerably at the open lubricant pocket regions without expected effects on the process [14,15]. However, in macroscale, lubricants are extensively utilised to enhance the product quality, to decline forming force and increase tools life-cycle.

To address these shortcomings, several studies have been conducted regarding lubrication in microforming especially micro deep drawing (MDD). Gong et al. [16] proposed the effects of polyethylene film, castor and soybean oil lubrication conditions. It was found that the polyethylene film is capable of reducing the maximum drawing force, increasing drawability and surface quality. Treated blank holder and die by film of diamond like carbon (DLC) were exploited and found drawing force decreases and flowability increases sufficiently [17]. Hu et al. [18] verified the results obtained by Gong et al. [16] and found the DLC-coated die is able to reduce friction coefficient and drawing force. Gong and Guo [19] proposed the effects of TiN, MoS₂ and DLC films as lubricants and found that the drawing force decreased and formability increased in the case of utilising DLC film. Shimizu et al. [20] applied a high power impulse magnetron sputtering (HIPIMS) deposition technique to process microforming die and found that the smooth surface and uniformity along three axes led to lower friction coefficient, drawing force, and increasing tool lifecycle. Gong et al. [21] studied effects of 4 lubrication conditions on pure copper C1100 in micro-conical-cylindrical cups, and found polyethylene film impacts the maximum force significantly in comparison with petroleum jelly, castor oil and dry lubrication conditions. As another approach, Sato et al. [22] applied fluid pressure in micro-Hydromechanical deep drawing (MHDD) and caused the fluid pressure remains in open lubricant pocket and found that by decreasing a specimen size, the friction coefficient decreases.

In this study, MDD process was selected to investigate influences of three lubrication conditions due to extensive use of cup-like micro parts, including dry, pure oil and TiO₂ oil-based nano-additive lubricants. The drawing force and formed cup quality under the mentioned lubrication conditions were investigated for Mg-Li alloy blank with thickness of 50 µm. As Mg-Li alloy is a novel material in microforming and its applications increase considerably [23,24], various heat treated types were generated and mechanical properties were obtained from micro tensile test. A simulation model was developed based on the mentioned lubrication conditions and obtained mechanical properties for each group and ultimately the simulation and experimental results were assessed and discussed.

2.Experimental

2.1.Heat treatment

Mg-Li alloy (Mg-9%Li-1%Zn) blanks with 50 ± 2 µm in thickness, which the composition is listed in Table 1, were heat treated to release residual stress and alter mechanical properties. Annealing was performed at various temperatures by KTL tube furnace under protection of argon gas due to the high flammability and preventing oxidation of the material. The cooling occurred in the furnace under the argon gas protection. According to the melting point of the alloy, three conditions were chosen

including heat treated at 150 °C for 30 min, heat treated at 200 °C for 2 hours and as-received form which was undergone hot rolling process.

Table 1 Composition of the Mg-Li alloy				
Element	Mg	Li	Zn	Mn
Mass percent (wt%)	Balance	8.95	0.97	0.1

According to the heat treatment temperatures, the blanks were categorised into three groups, and Table 2 lists the heat treatment details. The surface morphologies of three blanks were observed by a 3D laser scanning microscope as shown in Fig. 1. To measure the surface roughness parameters, a 3D laser scanning microscope, VK-X200 ©KEYENCE, was employed in which for formed micro-cups all measurements were held on the wall and for each condition measurements were repeated for 5 times. The surface roughness measurement and the coloured-height images illustrated that the heat treated at 150 °C for 30 min blank had the roughest surface, while the as-received blank surface was the most even.

Table 2 Different types of Mg-Li blank			
Groups	Temperature (°C)	Time (min)	Heating rate (°C/min)
1	As-received		
2	150	30	10
3	200	120	10

Fig. 1 The blanks surface morphologies, (a) a-received, (b) heat treated at 150 °C for 30 min, and (c) heat treated at 200 °C for 2 hours

2.2. Micro tensile test

To obtain mechanical properties of each type of Mg-Li blank for numerical study, tensile tests were conducted. Due to size effects, micro tensile samples with 50 μm in thickness and 1 mm in width were produced to reflect size effects on mechanical properties based on ISO 12086-2:1955 standard. The micro tensile test sample and related dimensions are illustrated in Fig. 2. Small size of the tensile test sample demanded to develop a new strain measurement method. Consequently, a precise non-contact strain measurement system was applied based on MATLAB image processing tool. To obtain high-resolution images, a microscope was utilised to record tensile sample elongation in a video format, then each frame counts as a picture. For further image processing, strong contrast between the sample gauge and background colour was required, accordingly the gauge region was marked precisely. Edge detection performs based on the defined thresholds of purpose colour and comparison between adjacent pixels. Once the gauge's edges were determined, their coordinates' changes can be calculated along length by the program. The comparison between the first frame and the elongated

gauge in the next frame, illustrates the elongation. In this stage, the cross section of the tensile sample and the elongation are known, accordingly the strain can be measured precisely.

Fig. 2 The micro tensile sample (a) marking of the gauge, and (b) dimensions

Instantaneously, force was recorded by a force cell and with respect to the number of video frames and the points from load cell can be matched. Therefore, both true and engineering stress-strain curves were plotted.

Fig. 3 True stress-strain curve for various Mg-Li types

The micro tensile test was repeated 5 times for each groups and the average value was plotted in Fig. 3. The mechanical properties of as-received, heat treated at 150 °C for 30 min and heat treated at 200 °C for 2 hours are listed in Table 3. The as-received Mg-Li sample was produced under hot rolling condition, accordingly grains refinement and high strength were expected from this group of material. For the heat treated at 150 °C for 30 min type, the heating temperature was relatively low and fine-grains remained at the structure [25] and led to the high flow stress. In the heat treated at 200 °C for 2 hours type the annealing effects were appeared by eliminating the strain hardening. In the other word, in the case of the as-received and the low heating temperature, the grains were not coarse but

fine and dense. Correspondingly, fine grains means more grain boundaries hence the amount of possible pile up at the boundaries reduces which leads to avoid dislocations movement and high deformation resistance [26]. According to the microscale size effects, due to a few number of grains along sample thickness, two phenomena were expected firstly, increase of data scatter due to the random mechanical properties of grains, secondly reduction in entire elongation because of limited number of grains.

Table 3 Mechanical properties of various types of Mg-Li alloy blanks

Types of Mg-Li alloy	Young's modulus (MPa)	Yield stress (MPa)	Ultimate tensile strength (MPa)
As-received	17472.71	175.93	193.83
Heat treated at 150 °C for 30 min	14510.55	183.82	191.32
Heat treated at 200 °C for 2 hours	10981.65	115.92	152.10

2.3. Micro Deep Drawing

The MDD system includes a servo motor with capacity of producing up to 25 KN to generate the drawing force, control box to adjust the MDD process and die sets to form the micro cups is shown in Fig. 4. The developed MDD system was combined with blanking stage in which, initially the die acts as blanking punch while the blank holder moves downward to cut the round blank. Blanking is the half stroke of the process and the next half is the micro cup forming stage and the key parameters of the MDD process is shown in Fig. 5. During the MDD process, punch is the part that moves toward the die with the speed of 0.1 mm/s. The blanking and drawing stages are performed continuously in one stroke. The mentioned three types of Mg-Li blanks were drawn under dry, oil and TiO₂ oil-based nano-additive lubrication conditions and each experiment was repeated 5 times.

Fig. 4 The MDD system includes MDD machine and control box

The lubricants were added into the blank, die and blank holder clearance due to the major friction force from the mentioned regions. The oil lubricant density was 0.9 g/cm³ at room temperature and the viscosity was 1.20 Pa.s at 23 °C and 0.18 Pa.s at 80 °C. The contained 1.0 wt.% Titanium dioxide nano-particle lubricant was provided by Wu et al. [27] and the composition and material properties are listed in Table 4. The TiO₂ nano-particles were approximately 20 nm in diameter and the mentioned oil was utilised as the dispersive solution. Initially, the TiO₂ nano-particles were mixed with the oil by mechanical stirring for 8 min at a high speed. Then, to breakdown remained agglomeration and enhance the dispersibility of the TiO₂ nano-particles, ultrasonic stirring was induced to the suspension for 10 min. The nano-particle lubricant illustrated proper stabilization in which the nano-particles remain suspended for days without sedimentation. The oil and dry lubrication conditions were studied as two benchmarks to evaluate the effects of the nano-particle lubricant.

Table 4 Composition and material properties of the 1 wt% oil-based nano-additive lubricant

1 wt% TiO ₂ oil-based nano-additive lubricant	TiO ₂ nano-particles (P25 provided by Sigma Aldrich™)	Size	20 nm
		Phase distribution	75% of anatase
			25% of rutile
	Oil (provided by BaoSteel Company)	Density	4.23 g/cm ³
		Viscosity	1.20 Pa.s at 23 °C
			0.18 Pa.s at 80 °C
		Density	0.9 g/cm ³

3. Simulation

In order to control and investigate the parameters of the process, the finite element method (FEM) was conducted. To study the MDD process precisely, the obtained mechanical properties from the mentioned micro tensile test were utilised. In this study, the explicit module was selected as the MDD is a dynamic process in which effects of velocity and time should be considered. To analyse the MDD process and deformation behaviour of the Mg-Li alloy in detail, incremental displacement and drawing force are required and the explicit module is capable of defining the increments small enough to ensure the precision of the analysis. A quarter of MDD process was modelled in ABAQUS due to the axisymmetric geometry of the process to accelerate analytical speed and reduce computational time and symmetric boundary conditions along straight edges of the blank were defined. High quality meshes were required due to the large deformation in microscale. Consequently, to enhance accuracy and competency in generating meshes, complete mesh integral elements were selected by high quality 8-node quadrilateral meshing in which total number of 11204 nodes and 8115 hexahedral elements of type SC8R were generated. The SC8R 8-node quadrilateral meshes in-plane continuum shell are advantageous for large deformations due to their quality and mesh seeds allocation on the edges of a microscale blank. The model consisted of three analytical rigid bodies including die, punch and blank holder and the blank as deformable continuum shell element. Fig. 5 shows the MDD model assembly and the schematic view of the dimension. The continuum shell element is the same as shell element but with consideration of continuum element topology which caused improvement in

geometrical structure of blank thickness. Fig. 6 shows a formed cup based on the equivalent plastic strain in which the mouth of the formed cups had the highest amount of permanent strain.

Considering the friction, the interaction properties were defined as tangential behaviour with penalty contact formulation and the metal forming specialised surface to surface arrangement was chosen as the interactions among bodies. The surface to surface arrangement defines the friction and contact force, accordingly the blank thickness as a primary parameter should be measured precisely for further results agreement. The trend of drawing force in simulation was similar to that of experiments, although the peaks' slight differences were occurred due to the surface characteristics of the blanks. In microscale, surface asperities are counted as part geometries while they can be neglected in macroscale.

Fig. 5 The MDD process, (a) model assembly, and (b) schematic view of geometries

The simulation was run for three types of Mg-Li under three lubrication conditions. The comparison of drawing forces in simulation and experiments are shown in Fig. 7 (a) as-received Mg-Li, (b) heat treated at 150 °C for 30 min Mg-Li and (c) heat treated at 150 °C for 30 min Mg-Li blank. Based on the ball-on-desk test, the friction coefficient of TiO₂ oil-based nano-additive lubricant was the lowest, listed in Table 5, which similarly to the experimental results, the maximum drawing force of simulation under the mentioned lubrication condition was the lowest in comparison to the oil and dry lubrication conditions.

Fig. 6 Formed cup in ABAQUS (a) Cup outer wall, and (b) Cup inner wall

Table 5 Friction coefficients under various lubrication conditions

Conditions	Friction Coefficient
Dry	0.07
Oil	0.04
TiO ₂ oil based nano-additive	0.03

Fig. 7 The comparison between the drawing forces in experiments and simulations, (a) Ac-received Mg-Li, (b) heat treated at 150 °C for 30 min Mg-Li, and (c) heat treated at 150 °C for 30 min Mg-Li blank

4. Results and discussion

To evaluate the effects of different lubrication conditions on three types of Mg-Li blanks, initially the behaviour of the material in MDD process were investigated. The maximum drawing force was plotted for three types of Mg-Li under three lubrication conditions in Fig. 8. Initially, the drawing force trend for all of the experiments increases with a low slope, then increasing the slope to reach a peak which is the maximum drawing force then declining with a relatively high slope to a non-zero value due to strain energy which is stored in the formed cups. The stored strain energy causes the formed cups springback to gradually release the stored strain energy. When the MDD is initiated, the dominated force is the bending resistance force due to the large deformation while the other forces including friction force are relatively small. By entering the blank into the die, gradually the friction force rises by increasing the contact area between the blank and the die. Subsequently in this while the drawing force surges to reach to the maximum. Accordingly, the effects of lubricants on the last stroke drawing force were studied to evaluate the lubricants effectiveness. Fig. 9 shows the comparison among last stroke drawing force for all of conditions. The maximum drawing force was reduced up to 14.14 % while the last stroke drawing force was reduced by 42.26 % in the case of applying TiO₂ oil-based nano-additive lubricant in comparison with dry lubrication condition. Although the reduction of both the maximum and last stroke drawing force was significant, the considerable reduction at the last stroke drawing force indicates the significant effect of utilising the nano-particle lubricant on the drawing force.

Fig. 8 The maximum drawing force comparison

As shown in Fig. 3, in the case of the heat treated Mg-Li at 200 °C for 2 hours, the Young's Modulus and flow stress were relatively lower than the other groups consequently the drawing force reached the maximum faster than the other groups and the growing trend of drawing force started earlier due to the lower bending resistance. While, the as-received group had the largest Young's Modulus and the flow stress consequently the maximum drawing force was expected to be the highest among the other groups while the results illustrated that the maximum drawing force of heat treated Mg-Li blank at 150 °C for 30 min was the highest under dry lubrication condition. Once the surface roughness of blanks and formed cups was compared, it was found that the surface roughness of the heat treated blank at 150 °C for 30 min was the worst. In microforming, due to the size reduction, the surface asperities remained constant accordingly the peaks and valleys are counted as a part of blank

geometry. Therefore, the blank heterogeneity affects the friction and its influence comes to be considerable in microscale.

Fig. 9 The last stroke drawing force comparison

The friction force is affected by the topology of the blank and tool interface which is called real contact area. The contact pressure on the blank is relatively high which is significantly influenced by tribological characteristic of the blank and tool interface. The surface roughness can be evaluated by the meaning of the arithmetic mean roughness (R_a) defined as Eq. (1), the skewness (R_{sk}) based on Eq. (2), and the mean of the maximum height of peaks and valleys (R_z) expressed as Eq. (3). The as-received blank illustrated better surface quality while the heat treated blank at 150 °C for 30 min had the poorest quality. As it is shown in Fig. 11, after MDD process, the R_a , R_{sk} and R_z were increased, although by utilising oil and TiO₂ oil-based nano-additive lubricants the surface quality was improved. The effect of the nano-particle lubricant was significant in which the R_a was reduced up to 18.18 % in comparison with dry lubricant condition. Fig. 10 shows the formed cups of as-received blank under dry, oil and TiO₂ nano-particle lubrication condition which can be seen by utilising the nano-particle lubricant the surface is more even in comparison with the dry condition.

Fig. 10 The formed cups of as-received blank under (a) dry, (b) oil, and (c) TiO₂ oil-based nano-particle lubrication condition

The R_{sk} indicated that the initial blanks mostly contained peaks while, the R_{sk} after MDD was negative which means valleys shaped most of the surface asperities. Generally, a negatively skewed surface is more effective for utilising lubricants. By utilising the 1 wt% TiO_2 oil-based nano-additive lubricant, the R_{sk} values tend to get closer to zero which points out the distribution of peaks and valleys becomes more even and the surface quality improves considerably. The heat treated blank at 150 °C for 30 min experienced the most improvement by the meaning of R_a due to the lowest skewness value. The skewness was increased by utilising the lubricants and the height distributions tend to be more symmetric around the mean plane.

$$Ra = \left(\frac{1}{L}\right) \int_0^L |Z(x)| dx \quad (1)$$

$$Rsk = \frac{1}{Rq^3} \left(\frac{1}{L} \int_0^L Z(x)^3 dx \right) \quad (2)$$

$$Rz = Rp + Rv \quad (3)$$

where, L is the evaluation length, $Z(x)$ is the height function of the measured profile, R_q is the root mean squared, R_p is the maximum peak height and R_v is the maximum valley height from average line.

Fig. 11 The surface roughness by the meaning of R_a and R_{sk}

The maximum roughness height (R_z) despite the R_a which merely reflects the deviations from the mean of the asperities, indicates the perpendicular distance from the lowest valley to the highest peak, consequently extremes influence this parameter greater than R_a . Therefore, once the maximum and the minimum R_z values get closer and reduce, it can be concluded that the surface is more even, smoother and the surface quality is increased. Fig. 12 illustrates the R_z value for before and after MDD process under mentioned conditions. The R_z value after MDD process was increased under dry, oil and nano-particle lubrication conditions, while utilising the lubricants caused a reduction in the distance between the lowest valleys to the highest peaks. The maximum R_z value reduced with higher slope which was notable in the case of as-received Mg-Li, accordingly it can be concluded that by applying the nano-particle lubricant due to the reduction of the maximum and minimum R_z value and getting closer the surface was smoother. As a result, by utilising the 1 wt% TiO_2 oil-based nano-additive lubrication condition the surface roughness improved and drawability increased substantially.

Fig. 12 The R_z value comparison

Comparing the thickness distribution along experimental and simulation micro-cup wall is used to determine the accuracy of the simulation model with the experimental micro-cups. Fig. 13 shows the thickness distribution along the micro-cup wall in the simulation and experiment. Since the trend for the difference was slightly similar for various types of blanks, as-received blank under oil lubrication condition was selected to illustrate the accuracy of the model and experimental results. Fig. 14 illustrates the position of the points mentioned in Fig. 13. In line with the experimental results, the formed cup in the simulation shows higher thickness at the cup mouth, by moving toward the cup bottom the thickness reduces.

Fig. 13 Comparison of thickness distribution along micro-cups in experiments and simulations

Fig. 14 Measured points position along cup wall (a) experimental, and (b) simulation micro-cup

The nano-particle lubricant illustrated higher efficiency in the experimental results that could be justified based on the open and closed lubricant pocket theory which expresses due to the increase in open lubricant pockets, lubricants overflow is dominant. Accordingly, more dense and viscose lubricants enhance the effectiveness of the process. In this study, the TiO_2 oil-based nano-additive lubricant had the higher dynamic viscosity and density by far subsequently, demonstrated superior performance in comparison with dry and oil lubrication conditions. The flow resistance of nano-particle lubricant in the open lubricant pockets caused more static behaviour to avoid overflow and

drain from the interface as schematically shown in Fig. 15. Hence, the friction size effect tends to be compensated by utilising the higher viscosity lubricant due to the higher flow resistance which leads to the overflow reduction at the open lubricant pocket regions, and the oil lubricant trapped at interface by nano-particles.

The considerable contact pressure on the real contact area at the blank and tool interface in microforming, especially MDD, has caused the tribological behaviour becomes crucial due to its great impact on the friction force, consequently total forming load. The surface roughness valleys were left on the formed-cups surface could trap the lubricants, while the nano-particles in the oil lubricant were also beneficial to storage the oil in the lubricant pockets and bear the contact pressure more effectively than the oil lubricant. Therefore, as shown in Figs. 7 and 8, the reduction occurred in the case of utilising the nano-particle lubricant can be justified by the mentioned mechanism.

Fig. 15 The schematic view of the mechanism of the nano-particle lubricant

Conclusions

Three heat treated types of Mg-Li blanks were drawn under dry, oil and TiO_2 oil-based nano-additive lubrication conditions and the corresponding simulations were conducted to control the parameters. The effects of the mentioned lubricants on drawing force and surface roughness characteristics were studied. The conclusions are as follows:

1. The drawing force was reduced by utilising the oil and nano-particle lubricants. The reduction was significant in the case of applying the nano-particle lubricant, in which the maximum force was reduced up to 14.14 % and the last stroke drawing force was reduced by 42.26 % in comparison with dry lubrication condition.
2. The simulation and experimental results were in a good agreement. However, when the surface roughness was increased a slight difference was appeared.
3. The surface roughness by the meaning of R_a , R_{sk} and R_z was considerably improved by applying the nano-particle lubricant. The R_a value was decreased up to 18.18 % in comparison with dry lubrication condition.

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References

1. Razali AR, Qin Y (2013) A review on micro-manufacturing, micro-forming and their key issues. *Procedia Engineering* 53:665-672
2. Xu ZT, Peng LF, Lai XM, Fu MW (2014) Geometry and grain size effects on the forming limit of sheet metals in micro-scaled plastic deformation. *Materials Science and Engineering: A* 611:345-353. doi:<https://doi.org/10.1016/j.msea.2014.05.060>
3. Qin Y, Brockett A, Ma Y, Razali A, Zhao J, Harrison C, Pan W, Dai X, Loziak D (2010) Micro-manufacturing: research, technology outcomes and development issues. *The International Journal of Advanced Manufacturing Technology* 47 (9-12):821-837
4. Qiu T, Hou YK, Cao H Review of Research Progress on Size Effect in Micro-Forming. In: *Key Engineering Materials*, 2017. Trans Tech Publ, pp 118-121
5. Sato H, Manabe K, Furushima T, Wei D, Jiang Z, Alexandrov S (2017) On the scale dependence of micro hydromechanical deep drawing. *Key Engineering Materials* 725:689-694
6. Irthia IK, Green G (2017) Evaluation of micro deep drawing technique using soft die-simulation and experiments. *The International Journal of Advanced Manufacturing Technology* 89 (5-8):2363-2374
7. Wang G, Li Y, Liu S, Yang J, Yang M (2018) Micro deep drawing of T2 copper foil using proportional decreased tools. *The International Journal of Advanced Manufacturing Technology* 95 (1-4):277-285
8. Han J, Zheng W, Wang G, Yu M (2018) Experimental study on size effect of dry friction in meso/micro-upsetting process. *The International Journal of Advanced Manufacturing Technology* 95 (1-4):1127-1133
9. Jahn SF, Müller B, Hilfinger FS, Schubert A (2016) Tribological impact of the finishing technology onto meso-and microforming processes. *Manufacturing Review* 3:4
10. Luo L, Jiang Z, Wei D (2017) Reprint of “Influences of micro-friction on surface finish in micro deep drawing of SUS304 cups”. *Wear* 376:1147-1155
11. Zheng W, Wang G, Zhao G, Wei D, Jiang Z (2013) Modeling and analysis of dry friction in micro-forming of metals. *Tribology International* 57:202-209
12. Ma J, Gong F, Yang Z, Zeng W (2016) Microdeep drawing of C1100 microsquare cups using microforming technology. *The International Journal of Advanced Manufacturing Technology* 82 (5-8):1363-1369
13. Wang C, Guo B, Shan D, Zhang M, Bai X (2014) Tribological behaviors in microforming considering microscopically trapped lubricant at contact interface. *The International Journal of Advanced Manufacturing Technology* 71 (9-12):2083-2090
14. Wang C, Guo B, Shan D (2014) Friction related size-effect in microforming—a review. *Manufacturing Review* 1:23

15. Luo L, Wei D, Wang X, Zhou C, Huang Q, Xu J, Wu D, Jiang Z (2017) Effects of hydraulic pressure on wrinkling and earing in micro hydro deep drawing of SUS304 circular cups. *The International Journal of Advanced Manufacturing Technology* 90 (1-4):189-197
16. Gong F, Guo B, Wang CJ, Shan DB (2010) Effects of lubrication conditions on micro deep drawing. *Microsystem technologies* 16 (10):1741-1747
17. Gong F, Guo B, Wang C, Shan D (2011) Micro deep drawing of micro cups by using DLC film coated blank holders and dies. *Diamond and Related Materials* 20 (2):196-200
18. Hu Z, Schubnov A, Vollertsen F (2012) Tribological behaviour of DLC-films and their application in micro deep drawing. *Journal of Materials Processing Technology* 212 (3):647-652. doi:<https://doi.org/10.1016/j.jmatprotec.2011.10.012>
19. Gong F, Guo B (2013) Effects of solid lubrication film on SKD11 in micro sheet forming. *Surface and Coatings Technology* 232:814-820
20. Shimizu T, Komiya H, Watanabe T, Teranishi Y, Nagasaka H, Morikawa K, Yang M (2014) HIPIMS deposition of TiAlN films on inner wall of micro-dies and its applicability in micro-sheet metal forming. *Surface and Coatings Technology* 250:44-51
21. Gong F, Yang Z, Chen Q, Xie Z, Shu D, Yang J (2015) Influences of lubrication conditions and blank holder force on micro deep drawing of C1100 micro conical–cylindrical cup. *Precision Engineering* 42:224-230
22. Sato H, Manabe K-i, Wei D, Jiang Z, Alexandrov S (2016) Tribological behavior in micro–sheet hydroforming. *Tribology International* 97:302-312
23. Jia W, Ma L, Le Q, Zhi C, Liu P (2019) Deformation and fracture behaviors of AZ31B Mg alloy at elevated temperature under uniaxial compression. *Journal of Alloys and Compounds* 783:863-876
24. Zhi C, Ma L, Huang Q, Huang Z, Lin J (2018) Improvement of magnesium alloy edge cracks by multi-cross rolling. *Journal of Materials Processing Technology* 255:333-339
25. Zou J-F, Ma L-F, Zhang G-H, Huang Z-Q, Lin J-B, Liu P-T (2018) Controlling Roll Temperature by Fluid-Solid Coupled Heat Transfer. *Chinese Journal of Mechanical Engineering* 31 (1):93
26. Zamani Z, Shishvan SS, Assempour A (2016) Stress gradient interpretation of boundary layers in passivated thin films. *International Journal of Non-Linear Mechanics* 81:139-146
27. Wu H, Zhao J, Xia W, Cheng X, He A, Yun JH, Wang L, Huang H, Jiao S, Huang L (2017) A study of the tribological behaviour of TiO₂ nano-additive water-based lubricants. *Tribology International* 109:398-408