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Effects of pre-process and post-process parameters on formability of magnesium alloys

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ABSTRACT

This paper highlights the basic characteristics of magnesium related to forming at elevated temperatures. The paper is divided into three sections. In the first section basic characteristics and applications of magnesium alloys are discussed, after then the focus is diverted to pre-processing and post-processing parameters including punch force, blank holder force, texture conditions, thickness and temperature distributions during forming, and springback effects. In the last section improvements in formability are highlighted by referring to forming limit diagrams to compare magnesium's performances with other alloys. By summarizing all these pre-processing and post-processing parameters directions are established to improve the formability of magnesium and guidance is provided for future research in this area.

Keywords: Magnesium; Formability; Limiting drawing ratio; Forming limit diagram; Post forming characteristics

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1. Introduction

The automotive industry is currently growing according due to increasing demand by markets in the developing world. Beside all the growth, this sector is also facing several problems from environmental conscious agencies. The most piercing demand is to reduce the emissions from vehicles and keep the environment clean [1]. Automotive researchers have suggested numerous solutions, which include variations in aerodynamic shape, increasing the efficiencies of engines or boosting the production of hybrid vehicles as well as abating the weight of vehicles [2].

Amongst all these solutions, a major step is to bring weight into line. After several studies, it is now an established fact that more than 50% of fuel consumption is mass dependent [3]. To attain this objective, numerous materials were considered like aluminium and titanium, but magnesium is getting more interest of researchers amongst the lightweight materials. At present the American manufacturers General Motors, Ford and Chrysler are using magnesium increasingly. General Motor is the leading company in the utilization of magnesium in its mirror brackets, transfer cases, instrument panels and steering wheels. Beside all these developments the use of magnesium is still only a fraction as compared to aluminium, which is reaching up to 123 kg per vehicle [4].

Magnesium is the lightest engineering construction metal and with a density of 1.74 g/cm^3 it is 35% lighter than aluminium (2.70 g/cm^3), and 78% lighter than steel (7.85 g/cm^3) [5]. Moreover it has average ductility, good recyclability, and improved vibration and noise characteristics as compared to other structurally used metals. In addition to that it is also tougher than plastics and electromagnetic interference (EMI) shielding and heat dissipation values are also much higher [6]. Magnesium alloys can be categorised into cast magnesium alloys and wrought magnesium alloys. Our focus in this paper will be confined to wrought magnesium alloys because of their increasing application in the sheet metal industry. Some of the well-known series in this category are AZ, ZK, WE and ZE. To improve the characteristics of pure magnesium several alloying elements are used, like in the AZ series aluminium and zinc are added to strengthen the workability of these alloys. Similarly in the ZE series rare earth elements like cerium, yttrium and neodymium are added along with zinc to increase the ductility of the material [7].

Beside all these applications and advantages there are some obstructions in the use of magnesium in mass production by the commercial sheet metal industry. The obstacle is its limited ductility at room temperature as compared to aluminium and steel. It is caused by the h_{cp} structure with few numbers of operative slips systems. This also reduces the melting point and makes it less resistant to corrosion [8].

To overcome aforementioned problems different techniques were presented. The most widely accepted solution is to improve ductility through elevated temperatures. This assisted the light metal industry and a technique named as superplasticity was suggested. T.G. Langdon defined superplasticity as the ability of a polycrystalline material to exhibit, in a generally isotropic manner, very high elongations prior to failure [9]. This method was first introduced on aluminium and titanium alloys, which show excellent ductility at higher temperature.

Superplasticity along with its advantages also has some restrictions. Some of the basic requirements of superplasticity are fine grained size material which means that grain sizes should be less than 10µm. The second restriction is slower strain rates which range from 10^{-2} to 10^{-4} s^{-1}. The third and the last limitation is an increased temperature i.e. the operating temperature should be approximately equal to $0.5T_m$ (where T_m is the melting temperature of the given material) [10].

Many researchers performed a number of experiments to overcome these problems. Since a slower strain rate is restricting utilisation in industrial applications, a technique was developed called HSRS (high strain rate superplasticity). Higashi [11] and his team achieved 280% elongation at a strain rate 10^{-2} s^{-1} for magnesium AZ91. Similarly Watanabe [12] and his team achieved 283% elongation at the same strain rate for ZK61. For the second restriction of grain size Wang [13] performed experiments on AZ80 alloy having a grain size of 35 µm and achieved 200% elongation at a temperature of 350°C. Similarly Bussiba [14], Watanabe [15] and Mubachi [16] also achieved low temperature superplasticity in magnesium AZ31, ZK60 and AZ91 respectively.

2. Formability of magnesium alloys

Formability is the ability of a material to undergo plastic deformation without damage or fracture. The plastic deformability of several alloys like hcp structured metals is quite limited in industrial applications [17]. Forming characteristics of magnesium alloys are not so widely investigated and most researchers have confined their studies to AZ31 which is the most common commercial magnesium alloy. The majority of the studies are related to uniaxial tensile tests at different temperatures, based on which many authors have made predictions about forming behaviour.

The warm deep drawing process is quite complex as it depends on a number of parameters that controls it [20] and requires a large number of tests (i.e. uniaxial, biaxial and multiaxial) and analyses to predict behaviour.

2.1. Experimental setup development

Warm deep drawing as already stated is a complex process to control as shown in Fig. 1. The heating of the blank is an additional step in this process. Two types are used for blank heating i.e. external heating and internal heating [22]. External heating which is commonly performed in an external oven is not effective in a laboratory procedure as heat losses can be great. However for industrial applications a conveyor system can be used in which heat losses will be minimized.

Internal heating is the preferred method as heat can be homogeneously distributed in the blank. The blank needs to be clamped by the blank holder for a short time to distribute the heat evenly from the heated tool. The drawing setup also involves setting of different processing parameters like temperature, punch velocity, ram stroke, and blank holder force (BHF). The drawing gap between the sheet and the die usually should be 1.2 times the sheet thickness [23].

2.2. Examination of the basic forming parameters

Increased drawing capacity of magnesium sheets not only tackles indirectly environmental issues through lightweight designs but also enhances productivity and quality of parts. A few studies are available regarding the drawing of magnesium sheets, some of which are Doege and Droder [21] who have performed limiting drawing ratio (LDR) experiments to examine the formability of AZ31 sheet at different temperature states and it is possible to form 100 mm diameter cups with LDR of 2.5 at a forming temperature of 200°C. Beside this they also mentioned investigating the forming of magnesium alloys in rectangular pans and achieving a maximum height of 65 mm at 225°C. One common fact found in both rectangular and round cups is that wrinkles in the drawing will decrease with an increase in the temperature up to a certain limit. Droder and Doege [24] also investigated that an increase of the formability of magnesium alloys is possible by establishing higher temperatures at the tool corners and lower temperatures at the tool's straight edges. By implementing this technique they formed a 110 mm x 220 mm x 1.0 mm sheet with a drawn depth of 98 mm. This is an increase as compared to experiments in [21] which also drew the same size of cup with a height of 65mm. Yoshihara et al.[22], Huang et al.[26] and Yoshihara et al.[25] have suggested a new combination of a local heating and cooling system to increase the formability of magnesium sheet. [25] has achieved an LDR of 5 by using a combination of blank holder pressure technique (BHP) and local heating/cooling system.

Heat treatment processes also influence the formability of magnesium alloys. Yang et al. [27] investigated the cold forming deformation behaviour of magnesium AZ31 by performing uniaxial tensile tests and deep drawing tests. They used a sheet thickness of 0.5mm and annealed these sheets at different temperatures varying from 400°C to 550°C for 1 to 3 hours and achieved an LDR of 1.72. It was also found that anisotropy effects are dominant during cold forming and vary material flow into the die cavity resulting in different thicknesses at the flanges for different orientations.

All these results are indicating that magnesium alloys can be commercially used as an alternate material for aluminium and steel by implementing all the above mentioned techniques and parameters. After summarising all these formability results in Table 1, a search was conducted for the optimization of process parameters and factors that are affecting formability of magnesium alloys, so that these alloys can compete with existing metals in the field of sheet metal forming especially in automotive and aerospace industries.

Influence of punch speed

Different factors that affect the drawability have been investigated by many researchers, like the effect of strain rate is discussed by Zhang et al. [28] who have conducted deep drawing at three punch speeds 7.5, 30 and 72 mm/min and proved that at increased strain rates ductility of magnesium alloys decreases drastically and causes draw-in of the flange which ultimately decreases its drawability [24] also focussed on this issue and showed a comparison of four magnesium materials and their trend of LDR against punch velocity at 200°C as shown in Fig. 2. All the four magnesium alloys demonstrated a similar trend that is a declination in LDR as the punch velocity increases.

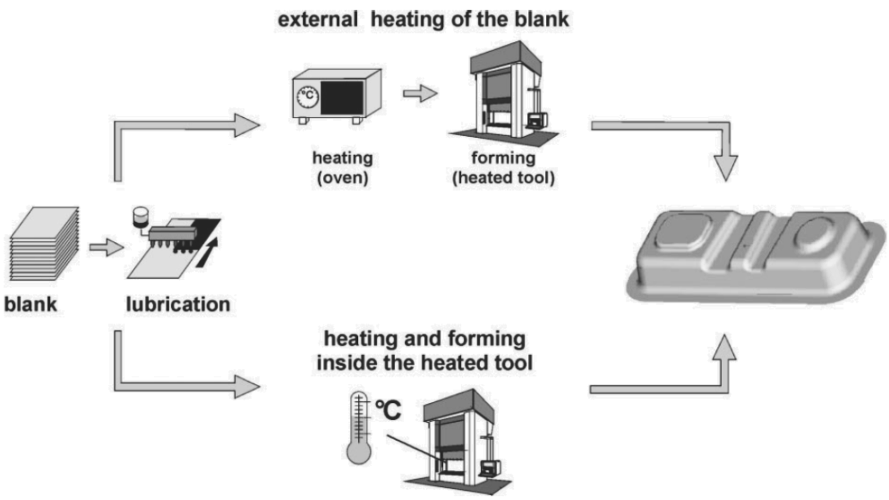

Fig. 1. Process diagram of deep drawing tests at higher temperature [21]

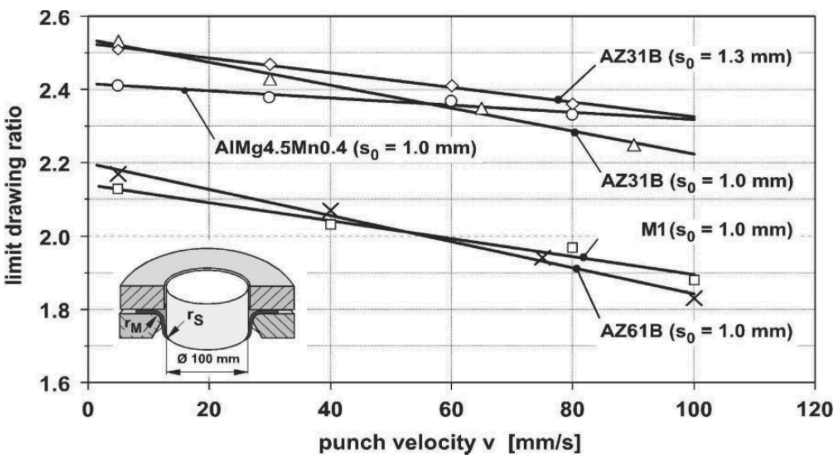

Fig. 2. Comparison of four magnesium alloys at different punch speeds [24]

Table 1.
Summary of LDR values of magnesium AZ31

Processed	Temperature	Thickness (mm)	Punch Speed	LDR	Reference
Rolled	50	1.0	100 mm/sec	1.5	21
	100			1.68	
	150			2.3	
	200			2.5	
	250			2.3	
	300			2.2	
Rolled	453 K	2.5	5 mm/min	2.2	22
	383 K			1.67	
Cross rolled + annealed	15°C	0.6	4 mm/min	2.0	31
	150-20°C		15 mm/min	2.5	
	200-30°C		15 mm/min	3.0	
	20°C	0.58		2.63	26
Hot rolled + annealed	180	0.7	30 mm/min	2.2	32
	180		15 mm/min	2.5	
	180		6 mm/min	3.25	
	23°C		30 mm/min	2.8	
	23°C		15 mm/min	2.8	
	23°C		6 mm/min	3.375	
Rolling+ annealing	40°C	0.5	200 mm/min	5	25
	498K	0.83	3 mm/sec	3.0	28
Hot rolled	RT	0.8	30 mm/min	1.3	
	50			1.5	
	100			1.7	
	150			2.2	
	200			2.65	
	250			2.3	
Extrusion + annealing	200	0.8	1000 mm/min	1.8	33
	216			2.0	
	226			2.2	
	236			2.15	
	300			2.1	
Cast + hot rolled	250	0.5	30 mm/sec	2.3	34
	300			2.7	
	350			2.3	
Rolling	100	0.6		1.4	35
	150			1.9	
	200			2.3	
	250			2.1	
	300			2.0	
Repeated Unidirectional bending (RUB) processed	RT			1.3	
	50			1.4	
	100			1.75	
	150			1.9	
	200			2.2	
	250			2.0	
	300			1.9	

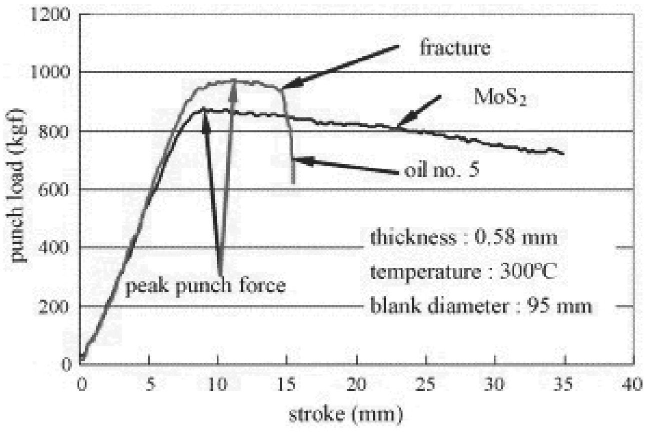

Fig. 3. Punch load vs stroke diagram [29]

The reason behind this declination is the generation of high stresses at low strain values. This trend also indicates that magnesium alloys are more sensitive to punch speed as compared to aluminium alloys.

Influence of the punch force

There are several factors that affect the punch force like temperature, stroke and blank diameter. The best drawability can be achieved when the punch force is less than the strength of the cup. Tyng et al. [26] described that by following above mentioned condition, successful flow of the blank in the die cavity can be achieved as shown in Fig. 3.

Yoshihara et al. [25] proposed a new strategy of variable blank holder force against a constant blank holder force and reported an improvement in the LDR from 2.09 to 2.14 at 300°C as shown in Fig. 4. It is also reported that thickening and thinning both are suppressed as compared to constant BHF in which thinning starts from the punch shoulder and extends to the wall and thickening occurs at the end site of the drawn cups.

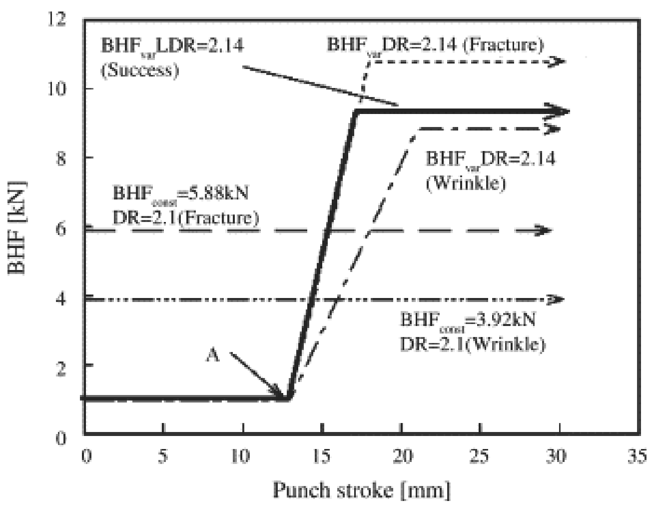

Fig. 4. Blank holder force vs punch stroke [25]

Influence of the texture (anisotropy)

The third factor as considered by Hua et al. [35] is the effect of texture on the drawability of magnesium sheets. It is suggested by many researchers like Watanabe et al. [36] and Huang et al. [37] that magnesium alloys possess strong basal texture which affects directly the ductility as well as the formability of these alloys. To improve its ductility and formability Iwanaga et al. [38] suggested that with reduction in texture, basal plane (0 0 0 2) formability of magnesium improved extensively from room temperature to 175°C. [35] Suggested a new method called repeated unidirectional bending (RUB) processing to soften the strength of magnesium AZ31. They rolled sheet several times on a long cylindrical rod with the help of supports and motors. After deep drawing tests it was concluded that the LDR of the sheets improved as shown in Table 1. They also found that the anisotropy ratio (r-value) which is quite low at higher temperatures (as it is also shown in uniaxial tests) is the possible reason of a declining LDR after 200°C.

It is also explained by Bohlen et al. [39], that mechanical anisotropy affects drawability of magnesium sheets extensively. The reason they showed is that most of the grains have their c-axes in the normal direction of the sheets in the basal type texture. So when load is applied in normal direction this will restrict the activity of the <a> dislocation slips and makes magnesium sheets difficult to form.

There are also several more ways suggested other than repeated unidirectional bending by Bohlen [39], Kocks et al. [40], Philippe [41] and Styczynski et al. [42] to tackle the anisotropy problem in magnesium sheets. The first method is to induce large shear deformation during rolling by the help of asymmetric rolling which makes texture quite weak. The second method suggested is the slight variation in chemical composition of the material by adding a little amount of rare earth alloys like yttrium (Y), cerium (Ce) or neodymium [43-50].

Influence of the temperature

This is the fourth factor that affects the drawability of magnesium alloys. L.M. Ren et al. [51] highlighted the variation in the drawing depth with temperature as shown in Fig. 5.

They explain that drawn depth increases with the increase in temperature up to 250°C and after it follows a decline in it, which results in local thinning in the formed cup as shown in Fig. 6. The possible reason for this declining trend in drawn depth against temperature is the lower work hardening exponent of the AZ31 sheets at higher forming temperature. Chen et al. [52] also stated that the optimum temperature for most magnesium sheets is between 200°C to 250°C.

The temperature distribution and its understanding is an important part of the forming process. Its understanding is necessary to predict the thinning and thickening of the sheet during forming. In the warm forming process when the punch travels towards the cavity in the die, the contact of the blank with the punch increases while the contact with the die decreases [53]. Due to this contact, the blank loses some of its heat energy to the punch. As a result of this the blank has a minimum temperature at the shoulder radius of the punch and an increased temperature at the shoulder radius of the die. Another reason for this is the low specific heat capacity and high thermal conductivity value of magnesium alloys which results in a significant difference in the punch and the blank temperature [54-55].

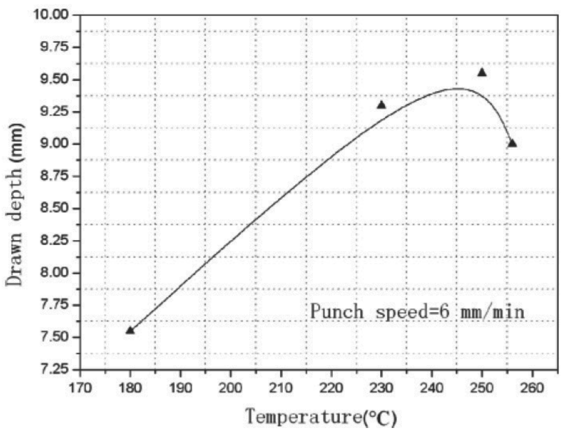

Fig. 5. Drawing depth of magnesium AZ31 at different temperatures [51]

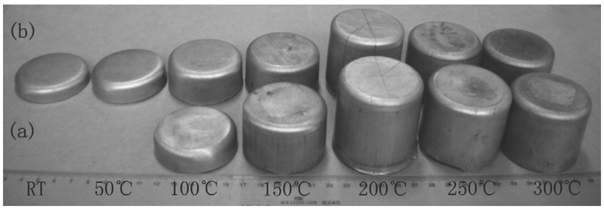

Fig. 6. Deep drawn cups of magnesium AZ31 at different temperatures [51]

[24] and [22] also state that due to this low temperature in the wall flow stress increases, so temperature controls are also an important parameter in drawability of magnesium alloys. A similar temperature distribution is also investigated by Hariharasudhan et al. [56] when they conducted forming tests of round shapes on magnesium AZ31B at 200°C. They observed an additional increase in the temperature of the flange which was set to 200°C. The reason stated for this increase is the amount of heat generation during plastic work. They also support the above reason that high flange temperature and low temperature in the wall are necessary for proper drawing of magnesium alloys as this will increase the flow stress and enable the cup wall to bear more stress at the punch corner. This strategy will also avoid localized necking in the material. They also explained the punch should always be kept at a lower temperature as compared to the blank because the punch temperature will automatically increase during the forming operation.

It is also necessary to mention here that the blank temperature is always a maximum at its corners because of less available area for convection as compared to the temperature along its side wall area where minimum temperatures are observed because of losses due to a large convection area and contact with the punch [56]. This will also help the forming operation. As we described earlier flow stress usually increases with decrease in temperature. So increased temperature at the corners avoids fracture and a large drawn depth can be achieved.

Thickness distribution during forming of magnesium alloys

The thickness distribution and its understanding is important for predicting the material behaviour during warm forming. Hariharasudhan et al. [56] investigated the thickness distribution for round and rectangular cups. In the case of round cups they observed maximum thinning in the cup wall both experimentally as well as in simulations. It is quite contrary to ordinary room temperature forming processes in which the maximum amount of thinning is usually observed at the punch radius. The reason for this different behaviour is the existence of non-uniformity in the strength of cup walls in warm forming as compared to ordinary cold stamping processes. This strength variation in the cup wall is related to the variation in temperature distribution in the cup wall as explained in the above section. The temperature is increased at the die corner radius compared to the punch corner radius which results in a lowering of the yield strength at the cup wall as compared to the material portion that is in contact with the punch corner which ultimately becomes the reason for thinning of the materials at the walls. The amount of thinning observed is 22, 15 and 20% against forming temperatures of 150, 200 and 250°C respectively.

It is predicted via FEA simulations that when thinning of materials exceeds 25% the specimen is considered a fail [56]. The comparisons of thinning regions at different temperatures are shown in Fig. 7 below.

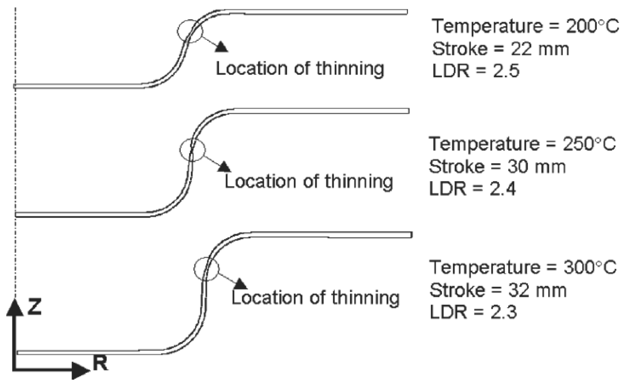

Fig. 7. Prediction of exact location of thinning area by FEA [56]

Springback properties in forming of magnesium alloys

Spring back effects are very critical to handle in hot forming processes. There are a few researchers who have investigated springback effects for magnesium alloys. Springback occurs on removal of load after completing the deep drawing process. The basic reason for its occurrence is the low elastic modulus of these sheets. There are several other factors that contribute to this effect like sheet thickness, material geometry, strain rate sensitivity, work hardening, yield stress and forming conditions [57,58].

Prediction of springback before the forming process is important because it creates dimensional inaccuracy which can create problems during assembly of parts [59] as shown in Figs. 8-10. Several yield criteria can be used to predict the springback effect like von Mises, Hill quadratic, Barlat's three parameters and Barlat 1996 [60-61]. Li et al. [62] investigated how elastic modulus and the hardening model affect the amount of springback in the sheet. Gau and Kinzel [63] highlighted the Bauschinger effect on the accuracy of the springback and proposed a new hardening model for prediction of the behaviour of the material. It is also confirmed by several authors that the amount of springback will reduce with the increase in temperature and almost vanishes at 300°C [64-66]. The possible reason for this is the decrease in the flow stress with increase in temperature.

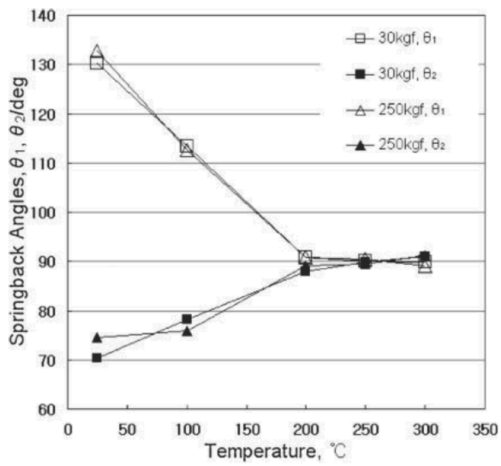

Fig. 8. Springback angles vs temperature during isothermal tests [69]

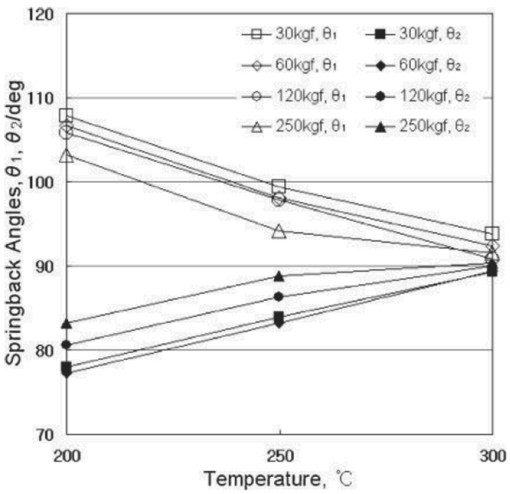

Fig. 9. Springback angles vs temperature during non-isothermal tests [69]

The effect of texture is also investigated by a few authors like Gomes et al. [61] and Ragai et al [67]. All have agreed that the amount of springback increases with the increase in the angle of rolling direction in aluminium and steels. This effect of texture on the amount of springback hasn't been considered by any researcher for magnesium alloys. So this is an area which requires attention of researchers in the future.

Takayuki et al. [68] investigated the springback characteristics in draw-bending of magnesium AZ31B sheet. They observed the amount of springback decreases with an increase in temperature and blank holder force (BHF), but temperature influences dominate the BHF.

Hyung et al. [69] performed draw-bending experiments with two different approaches named as isothermal tests and non-isothermal tests. In the isothermal tests they achieved a thermal equilibrium between blank holder, punch and die while in the non-isothermal tests die and blank holder are heated up to a desired temperature but the punch was not heated. They concluded after the tests that the springback effect is negligible at 200°C only in isothermal tests. But on the other hand it does not vanish in non-isothermal tests even at 200°C or above. So while conducting non isothermal draw-bending tests the springback effect must be taken into account during design of experiments.

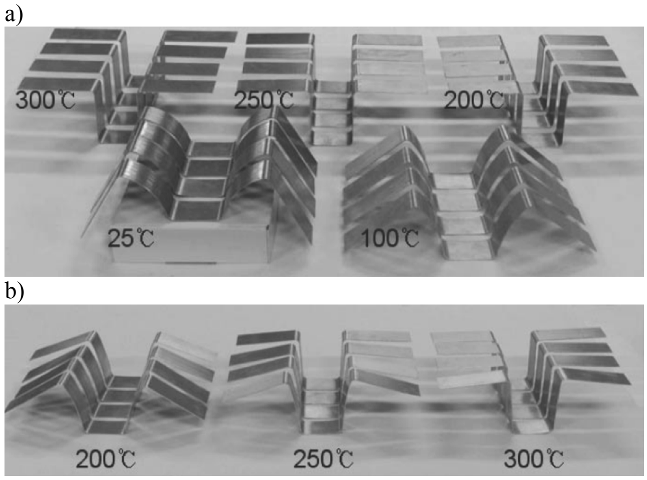

Fig. 10. Draw bending tests (a) isothermal tests (b) non isothermal tests [69]

Tooling geometries influences in forming of magnesium alloys

Tooling geometries include die clearances and punch radii etc. Proper die clearances are very important especially for thin sheets. In the case of smaller clearances fractures most commonly occur while on the other hand wider clearances will lead to appearance of wrinkles in the work-piece [69-71].

It is also reported that by using smaller punch radii formability of magnesium alloys is reduced. The reason behind this is smaller radii restrict material to flow simultaneously in different directions which ultimately leads to fracture because of an increase in major strains [60].

Other influences

Other factors including lubrication, initial blank shape and tooling geometry have also a strong influence on the formability of magnesium alloys. All above factors are indicating that optimization of all these factors will lead to an increase in the formability of magnesium alloys. This is a wide area available for researchers to vary all above mentioned parameters to achieve an increased formability of magnesium alloys.

Beside this different alloys need to be researched so that a maximum number of alternatives can be produced by the light metal industry as compared to aluminium and steel.

3. Forming limit curves (FLC) of magnesium

Formability of sheet metal is often assessed by forming limit diagrams (FLD). A forming limit diagram is a plot of maximum principal strains that can be sustained by sheet materials prior to the onset of localized necking. The concept of forming limit diagrams was introduced by Keeler and Beckofen in 1964 [72]. The FLD forming limit curve (FLC) represents the maximum major principal strains that can be reached in sheet materials at given minor principal strains prior to the onset of localized necking.

To check the formability of materials two types of tests are used i.e. the Nakazima test (Limit Dome Height test or LDH test) [74] and the Marciniak test. These tests are also called out-of-plane and in-plane forming tests. This is because in Nakazima tests strains are measured on the outer plane of the samples which is quite difficult while in the Marciniak tests the strains are measured on the inner surface of the material. Marciniak tests are very simple but still several industries also use Nakazima tests.

There are two major differences in these two tests as shown in Fig. 11. In the Nakazima test a hemispherical punch with a draw bead is used to form the blank. The beads are used to control the sliding motion of the blank. On the other hand Marciniak used a hollowed cylindrical shape with a flat head. In addition to this a specific blank is used with a drilled hole (pole region) at its centre also called as the driving blank. Due to this hole the force of the punch is concentrated at the centre of the blank as tensile (expansion) strain.

Emilie et al. [73] performed both in-plane and out-of-plane measurements on magnesium AZ31B and obtained an enhanced ductility at elevated temperature. They also reported that a 67% plane strain forming limit was obtained at 300°C. Also It was concluded it is difficult to perform out-of-plane (LDH) tests because of bending strains, frictional effects and normal pressure act on the magnesium sheets. Because of these effects LDH tests always show higher forming limits as displayed in Fig. 12 and Marciniak tests are the preferred method for identifying forming limits. But on the other side strain localization and occurrence of fracture near the pole is difficult to achieve in Marciniak tests.

There is still a gap of research to develop a methodology in which fracture and strain localization should be forced to occur near the pole. This can be done by optimizing the tool geometry parameters and temperature distributions in the experimental setup for performing FLD tests related to magnesium alloys.

Similarly Palumbo et al. [75] investigated forming properties of a magnesium alloy by varying temperature and strain rate based on the Marciniak method. They observed that by reducing the strain rate from 0.02 s^{-1} to 0.002 s^{-1} the forming limit curve of magnesium alloy shifts upwards by about 35% at 200°C. Huang et al. [35] also reported that FLC of magnesium alloys shifts upwards with an increase in temperature which indicates improvement of stretch formability. They also investigated the effect of repeated unidirectional bending which further improved its forming characteristics.

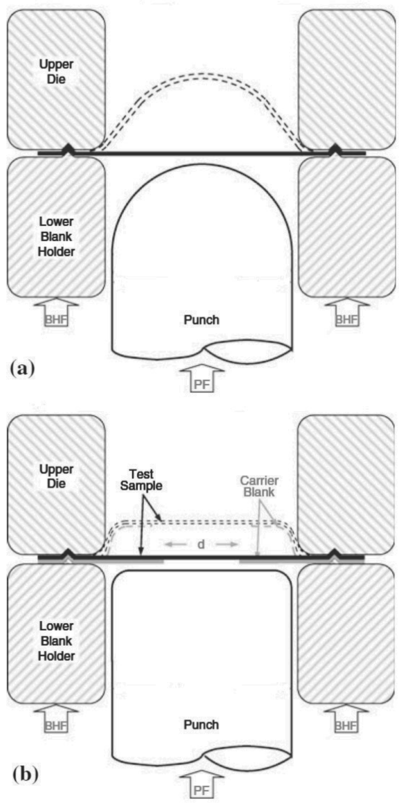

Fig. 11. a) Nakazima test setup, b) Marciniak test setup [74]

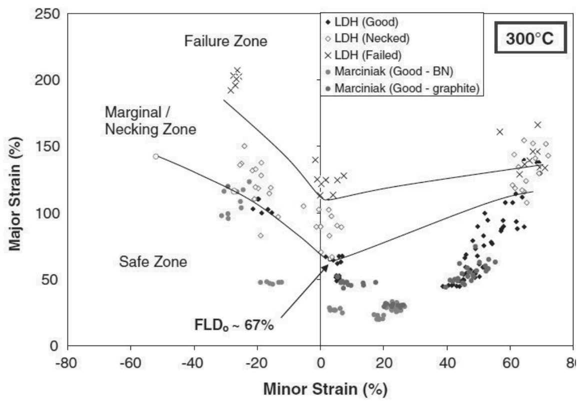

Fig. 12. FLC curves of AZ31 for Nakazima and Marciniak test [73]

All these references indicate that temperature, strain rate and other parameter have a strong influence on forming limit curves and their behaviour. There is a need to optimize these parameters to predict the exact behaviour of magnesium alloys to identify the fracture and safe zones.

4. Conclusion and future directions

In the current paper magnesium formability is discussed along with its pre-forming and post-forming characteristics. It can be concluded that magnesium alloys have good formability between 200°C to 300°C at lower punch speeds. However different process parameters can be varied to improve the formability.

Beside all above discussions magnesium alloys are still difficult to form at commercial level. To improve the formability a study is now being conducted by the authors into microstructural characteristics to understand the behaviour and flow of the material to maintain uniform temperature and thickness distribution during forming. Process parameters need stronger control during forming. It should also note that by varying blank holder force, further enhancement in the formability is possible. Punch temperature should always be kept lower than sheet temperature and the recommended difference is 50°C to 90°C for non-isothermal deep drawing tests. This will also reduce flow stress in the flange of the formed part. Springback effects are also important at warm temperature especially in non-isothermal tests.

Texture effects during forming need more attention to improve the formability. Basal type texture has a strong influence on the formability of AZ series wrought magnesium alloys and basal plane inclination is a major factor that needs to be examined accurately to improve formability. For more accuracy in drawing of forming limit curves, a more detailed study is required related to frictional effects and bending strains in both in-plane and out-of-plane test methods.

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