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Formability of Magnesium Alloys

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ABSTRACT: *In recent decades, an interest in magnesium (Mg) alloys has progressively increased in numerous industrial fields. Magnesium alloys are characterized by favourable strength/weight ratio thus representing a valid alternative to aluminium alloys and High Strength Steels, largely adopted in those sectors where the production of lightweight parts is an important requirement (aerospace and automotive industries, electronics and sport).In order to produce Mg components with better mechanical properties, dimensional accuracy and finishing quality, sheet metal forming processes are the best manufacturing choice. Since the ductility of Mg alloys is quite poor at room temperature, the formed products of magnesium alloy is still limited. In order to find the forming method and conditions suitable for the sheet, the forming limit, i.e. the fracture initiation in sheet forming processes, has to be correctly predicted. Efforts were made to optimize process parameters by analyzing the causes of defects in order to improve the Limit Drawing Ratio of magnesium alloy work pieces. In recent years, quite a few efforts have been made to study the methods for improving the formability of wrought magnesium alloy. A great deal of research in literature confirms the effectiveness of the process parameter temperature in improving formability. A Brief overview in the field of forming operations at elevated temperatures has been reviewed to summarize the formability of magnesium alloy sheet. As, AZ31 can be more effectively formed to obtain complex geometries, which is usually measured evaluating the material formability as the locus of limit strains ,more focus has been given to this alloy in the present review.*

Keywords: *AZ31, Forming Limit, Limiting Drawing Ratio, Magnesium alloy, Sheet forming*

I. INTRODUCTION

Magnesium alloy sheet was used in manufacturing, military, aircraft during and after the Second World War. They are used today in the automotive industry, mainly in sand and die castings; the development of light-weight vehicle is in great demand for enhancement of fuel efficiency and dynamic performance. The vehicle weight can be reduced effectively by using lightweight materials such as magnesium alloys. The low density of magnesium makes it ~35% lighter than aluminum and ~78% lighter than steel. Hence, successful implementation of magnesium in transportation industries would bring significant weight-saving benefits. Due to its lightweight and high specific strength, magnesium alloy have been considered as a promising alternative for high-strength steel and aluminum in some applications and has been widely used for structural components in the aerospace, electronics, and automobile industry to replace some existing materials[1, 2]. Because of lower density, better collision safety property and electromagnetic interference shielding capability, magnesium alloys are available for producing some structural parts such as the coverings of mobile telephones, notebook computers and portable mini-disks (MD). In the past, the demand for this alloy as a structural material was not high because of its less availability commercially as well as limited manufacturing methods. However, the use of magnesium alloys in sheet forming processes is still limited because of their low formability at room temperature and the lack of understanding of the forming process of magnesium alloys at elevated temperatures. The application of formed magnesium wrought alloys components, however, is restricted due to lack of knowledge for processing magnesium alloys, especially forming process, at elevated temperatures. However, since its alloy is a hexagonal close-packed metal and has poor formability, the formed products of magnesium alloy is still limited. In order to find the forming method and conditions suitable for the sheet, the forming limit, i.e. the fracture initiation in sheet forming processes, has to be correctly predicted. Therefore, previous studies [3–7] have been performed to summarize the formability of magnesium alloy sheet .Moreover, during the forming process, heat is generated by plastic deformation and the heat loss by conduction and by radiation and convection to the punch as well as to the environment can result in several property changes of the work piece. Therefore, this underscores the need for accurate methods to investigate a forming process of magnesium alloy not only deformation behavior but also heat transfer process, a task to which the finite element method is well suited. Finite element method (FEM) is a very effective method to simulate the forming processes with accurate prediction of the deformation behaviors.FEM can be used not only in the analysis but also in the design to estimate the optimum conditions of the forming processes. This can be done before carrying out the actual experiments for an economical and successful application of SPF to industrial components [8].

II. FORMABILITY OF MAGNESIUM ALLOYS

Magnesium possesses poor formability, difficult to be deformed at room temperature because of its hexagonal closed packed structure. It is necessary to enhance the forming temperature in order to improve formability of magnesium alloys effectively [9]. The research group has studied sheet metal forming processes of magnesium alloys in recent years [10–13] and found the mechanical properties of magnesium-alloy can be improved at elevated temperatures [14–18]. In this formability of magnesium alloy (more focus been given on AZ31 sheets) investigated by the experiment and FE analysis , various process like stamping, warm drawing ,deep drawing , friction Stir processing, Mg produced either by direct chill or twin roll continuous casting have been taken into account. Popular process used in assessment of formability of sheet metal is reviewed to determine the optimal processing parameters and explore novel forming technique [19, 20].

Fuh-Kuo Chen, Tyng-Bin Huang [21] conducted various experiments to study the formability of stamping magnesium-alloy AZ31 sheets of 1.2mm thickness at elevated temperatures. The mechanical properties of magnesium-alloy AZ31 rectangular specimens having the constant length of 140 mm, but with different widths ranging from 20 to 140mm in an increment of 20 mm, were tested at various temperatures ranging from room temperature to 400˚C. A heating furnace was mounted on the MTS810 test machine and tensile tests at elevated temperatures were performed. Forming characteristics of AZ31 sheets, such as forming limit, conical cup value (CCV), spring back and minimum bending radius, were also examined by experiments. The stress–strain relations indicated that AZ31 sheets had higher yield stress and smaller elongation at room temperature, but the yield stress, the work-hardening coefficient *n*, dropped significantly when the sheet was heated to a temperature higher than 200˚C.The experimental results showed that AZ31 sheets exhibited poor formability at room temperature, but the formability was improved significantly with greater possibility of local deformation, at elevated temperatures as in Fig.1 The sheets sustained more deformation before fracture at elevated forming temperatures The V-bend tests revealed the spring back was reduced when AZ31 sheets were stamped at higher temperatures. In addition, the conical cup value (CCV) tests performed in the present study revealed that an optimum forming temperature, which was below 400 ˚C, existed, and a lower forming temperature has to be applied in the actual forming process.

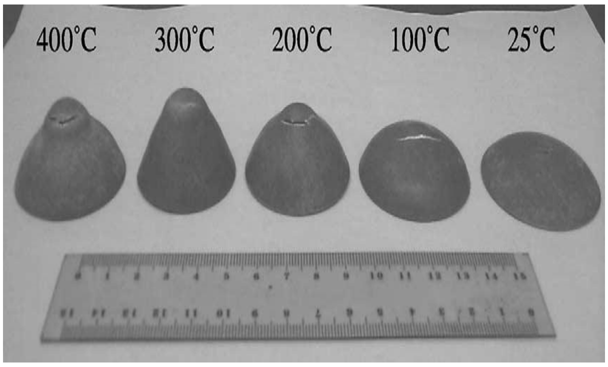


Fig.1.Fractured conical cups obtained from various temperatures.

In 2003, the square cup drawing of magnesium alloy AZ31 (aluminum 3%, zinc 1%) sheets was studied by experimental approach and the finite element analysis (The finite element software PAM STAMP). The mechanical properties of AZ31 sheets with 1.2 mm thickness according to the ASTM standards, at various forming temperatures were first obtained from the tensile tests and the forming limit tests. The test results in [22] indicated that AZ31 sheets exhibited poor formability at room temperature, but the formability could be improved significantly at elevated temperatures up to 200˚C. The finite element simulations investigated the effects of process parameters, such as punch and die corner radii, and forming temperature, on the formability of square cup drawing with AZ31 sheets. The other simulation parameters were: die clearance of 0.6 mm on each side, blank-holder force of 2.5kN, coefficient of friction of 0.1, and punch speed of 3 mm/s. In order to validate the finite element analysis, the deep drawing of square cups of AZ31 sheets at elevated temperatures was also performed. Both the tensile tests and the forming limit tests showed an inferior formability of AZ31 sheets if formed at room temperature. The formability dramatically improved when the AZ31 sheet was stamped at elevated temperatures. The punch radius (R_p) of 5 mm, die radius (R_d) of 6 mm, and corner radius (R_c) of 8 mm were the tooling dimensions used in both the finite element simulations and the experiments, both the finite element results and the experimental data revealed an optimum forming temperature of 200^0C for the drawing of square cups, with 0.5 mm thick AZ31 sheets. This optimum temperature may vary with the sheet thickness and the part geometry to be formed. The finite element simulation results indicated that a larger punch radius allowed for a uniform material flow toward both of the two principal directions under the punch profile at corners delayed the occurrence of fracture and a smaller punch radius reduced the formability of square cup drawing,. This strain-path pattern explained the reason why a larger punch radius leads to a better formability for the drawing of square cups. An optimum die corner radius for the drawing of square cups was also determined by both the finite element analysis and the experimental work. The investigation revealed that the formability improved as the die corner radius increased up to an optimum value, and became worse when the die corner radius was further increased. The strain path analysis indicated that the deformation of the sheet at the fracture location changed into the plane-strain mode from the stretch mode as the die corner radius was further increased from the optimum value, resulting in an early fracture since the plane-strain mode had a lower forming limit The experimental data showed a good agreement with the simulation results, and the optimal forming temperature, punch radius and die corner radius were then determined for the square cup drawing of AZ31 sheets.

In this study [23], non-isothermal finite element (FE) simulation (DEFORM 2D and 3D, coupled thermo elastic–visco-plastic commercial FEM codes) has been conducted for forming round cups and rectangular pans from Mg alloy AZ31B sheet at elevated temperatures. The results were compared with experiments, conducted at the Technical University, Hanover. Load–stroke curve, thickness distribution and temperature distribution in the sheet obtained in experiments [24, 25] were compared with FE simulation results for various forming temperatures. The flow stress for the calculated strains, temperature and strain rate were logarithmically interpolated and extrapolated using the available input data. The friction coefficient, μ, used in the simulations was obtained from the strip draw test conducted by Droder [24] and Doege et al. [26] and it was assumed not to vary locally with interface temperature and pressure. The interface heat transfer coefficient was assumed to be uniform for the entire surface and the value was selected based on the results published in the literature [27]. The forming load predicted by simulation for round cup and rectangular pan overestimated the experimental results. The trend predicted by simulation matched well with experiment. Higher punch force in the simulation could be due to the high frictional shear stress at interface. Coulomb friction coefficient of μ = 0.1 was used in the simulation. Von Mises yield criteria was used in simulation to describe the yield surface of Mg alloy sheets. In the warm sheet forming of round cup and rectangular pan, the maximum thinning and tearing was observed at the cup wall in simulation and experiment. This was contrary to the observations in conventional stamping where the thinning occurred in the punch corner radius. This could be due to the fact that the cup walls in warm forming were at high temperature compared to punch corners, thus, the yield strength of material in cup wall was low compared to punch corner radius. A maximum thinning of 30% was observed in the simulation as compared to 10% in experiment. Excessive thinning observed in the simulation could be due to high process loads observed in simulation as compared to experiment. Simulation and experiments predicted increase in limiting draw ratio (LDR) with increase in temperature. Maximum LDR was obtained at the forming temperature of 200˚C. LDR predicted by simulations for round cup for different forming temperatures were lower compared to the experimental results. Thermo-elastic–visco-plastic FEM code used in this study could successfully capture the deformation modes and the specific characteristics of the warm sheet forming process. At 300˚C, the cup failed at the stroke of 32 mm. T he maximum punch load obtained at all the simulated temperatures for LDR 2.3 was higher than the load obtained in experiment for corresponding temperatures. FE simulation results agreed well with experimental observations.

Tyng-Bin Huang et al. [28] studied the formability and non-isothermal deep drawing at elevated temperature of magnesium alloy AZ31B sheets by experiment and finite element analysis. The forming temperature, lubricant and sheet thickness was considered in this study. The peak punch force was increased as the diameter of blank increased. When the peak punch force was higher than the limit strength of the cup wall, the blank fractured, and the punch force decreased suddenly. The experimental results indicated that the highest limit drawing ratio (LDR) was at a forming temperature of 260˚C for 0.58mm thick AZ31B sheet, and the highest LDR 2.63. The highest LDR was at a forming temperature of 200˚C for 0.50mm thick AZ31B sheet, and the highest LDR 2.5 as shown in Fig.2 and Fig.3.The experimental data showed a good agreement with the simulation FEM code MSC Superform.

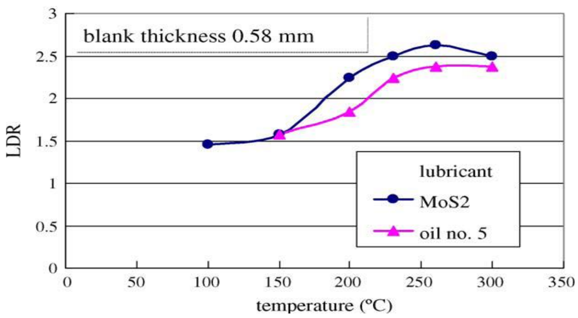


Fig.2. LDR from experiments at various forming temperature.

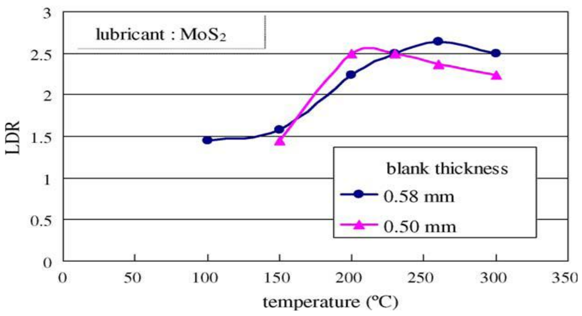


Fig.3. LDR of various sheet thickness from experiments.

In the research of [29], the forming limits on various forming process have been investigated using the experimental and FE analysis. Square cup drawing and stamping processes were used to investigate the formability of AZ31sheet of 1.5mm thickness according to the ASTM standards. The mechanical properties of magnesium alloy AZ31 sheets at various temperatures ranging from room temperature to 400˚C were obtained from experimental results and measured tensile properties were used to simulate the forming simulation by FEM commercial program, LSDyna^{TM}. The forming limit curve calculated based on the measured tensile properties could predict the fracture of formed part by FEM analysis. It showed some better formability at 400˚C forming temperature. Fracture at 400˚C forming temperature occurred by the diffuse necking due to the lower formability, because the work-hardening exponent was lower than that of 250 ˚C forming temperature. The best formability at 250 ˚C has been caused to the vital dynamic recrystallization as shown fig4**.** These experimental results well coincided with the FE analysis results predicted using the forming limit diagram (FLD) calculated by Keeler equation.

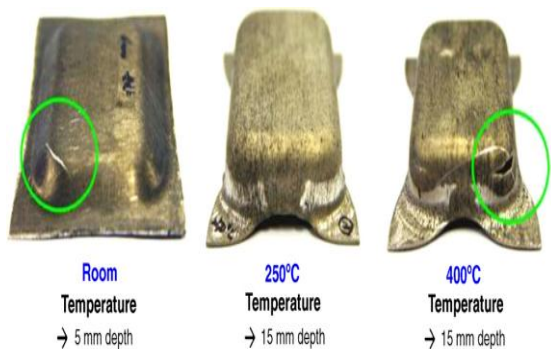


Fig.4. Square cups formed at each forming temperature.

A proper forming temperature range was determined in [30]. The effects of blank holding forces on the work piece quality were analyzed by warm deep drawing of cups from magnesium alloy sheets. Appropriate process parameters were selected to avoid forming defects effectively. In the paper, a rigid blank holder was used to adjust blank holding forces, using a 100 tonnes four-post multifunctional hydraulic press. A special liquid lubricant PTFE on the tool surfaces, punch diameter 65.6 mm/66.6 mm, punch shoulder radius 5 mm, die hole diameter 68mm and die shoulder radius 10 mm was used. The conditions of process defects, flange wrinkling and ruptures were analyzed. Experiments were carried out to verify the computer simulation results. Efforts were made to optimize process parameters by analyzing the causes of defects in order to improve the Limit Drawing Ratio of magnesium alloy work pieces. Computer simulation with explicit finite element method was used to optimize the process parameters before carrying out the actual experiments. It was found that rolled magnesium alloy sheets had good deep drawing formability at a forming temperature range of 105–170˚C with the limit drawing ratio up to 2.6. The cup of 0.4mm thickness had also been formed at this temperature. Some values greater than original thickness indicated the thickening on the flange. Formability would be reduced severely by excessive heating duration for a period of over 10 min in the preheated tools. Efforts were made to optimize process parameters by analyzing the causes of defects in order to improve the limit drawing ratio of magnesium alloy work pieces.

In the research work [31], an AZ31magnesium alloy sheet with excellent performances was fabricated by the cross-rolling and the uniform annealing treatments with annealing temperature 300^0C and the holding time 1 h. The uniaxial tensile tests were conducted using a Gleeble 3500 thermal–mechanical simulator, and the mechanical properties of AZ31 magnesium alloy sheet were analyzed. Limiting drawing ratio (LDR) experiments were performed on double-acting hydraulic press. The uniaxial tensile tests showed that AZ31 magnesium alloy sheet was sensitive to the deforming temperatures and strain rates. The elongation increased from 18% to 50% with increasing temperatures from room temperatures to 200^0C, and even reached 100% at 400^0C. It was also found that the ductility of AZ31 magnesium alloy sheet increased sharply with the decrease of strain rates. The experiments showed that the LDR reached 2.0 at the forming temperature of 150^0C and the drawing velocity of 15 mm/s. The AZ31 magnesium alloy sheet showed good formability at the temperature between 200 and 300 ^{0}C, LDR reached 3.0. The influences of drawing temperature and blank holder force on the formability are numerically investigated. A warm deep drawing process simulated by commercial explicit finite element code LS-Dyna demonstrated that variable blank holder force technology improved the LDR from 3.0 to 3.5, and decreased the wall thinning ratio from 15.21% to 12.35%.

ZEl0 magnesium alloy sheets were prepared through ingot casting and the hot-rolling process. The mechanical properties, conical cup value (CCV), bore expanding performance, and limit drawing ratio *(LDR)* were investigated by [32] to examine the stamping formability of ZEl0 alloy sheets, at temperatures ranging from 200 to 300 C. Tensile tests were carried out on SANSCMT5105 testing machine. The results showed that the tensile strength decreased, whereas, plasticity, drawing-bulging performance, bore expanding properties, and deep drawing performance increased markedly at elevated temperatures. The *CCV* tests were performed on the universal testing machine according to the GB/T 15825.6-1995standard.The CCV specimens could be drawn into the conical die' s underside cylindrical hole from the conical cliff, without cracking, and could have the minimum CCV at 200 and 250^0C . In the bore-expanding test, the bore (diameter 10mm) could be expanded to the dimension of the punch (dia. 25 mm) and the maximum bore-expanding ratio could be achieved at above 150 C as in Fig.5. The limiting drawing ratio *(LDR)* of 2.85 was acquired during the deep drawing test at 230 ^{0}C as shown in Fig.6.with the punch temperature of 20 - 50 ^{0}C, the punch velocity of 50 mm * min^{-1} and the mixture of graphite and cylinder grease as lubricant.

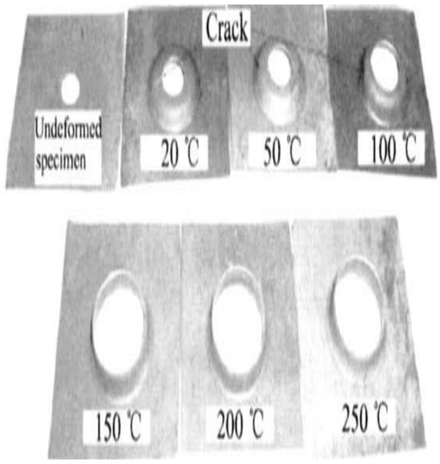


Fig.5 Specimens after bore-expanding tests at various temperatures

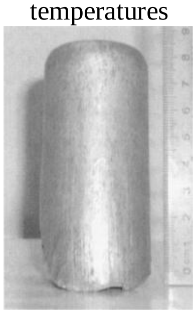


Fig. 6 LDR cup specimen at 230 C

Hai et.al [33] studied the deformation behavior of a cylindrical deep drawing of magnesium alloy sheets at elevated temperatures. Simulation was carried out by using a non-isothermal finite element based on DEFORM 3D commercial software. The experiments were conducted with a punch diameter of 40 mm, punch radius of 4 mm, die parameter of 42mm and die shoulder radius of 4 mm. The blank holder force was kept constant at 14 k N and the punch speed was 3mm/s. The tests were carried out at temperatures of tooling (die and blank holder) ranging from 423 to 523K while the temperature of punch was set at 298K. Teflon sheets were used as lubricant**.** In order to validate the finite element analysis, deep drawing test of cylindrical cup of AZ31 and AZ52 rolled sheets at given conditions was also performed. The LDRs of AZ31 and AZ52 increased with increasing in forming temperature and obtained the maximum values 3.2 and 2.8 at 498 K. the LDRs predicted by simulation were slightly lower compared to the experiment results. The punch force predicted by FE simulation overestimated the experiment results. This could be either due to high blank holder force and/or high shear stress caused by interface friction coefficient. The thermo-viscoplasticity FEM code, particularly Deform3D code could successfully capture the deformation behavior and specific characteristics of the warm sheet forming process. Maximum thinning of 32%

was observed in the simulation as compared to 27% in experiment. Thinning in the cup walls was greater than at the punch corner.

Forming limit diagrams were determined for a LZ61 alloy sheet with a thickness of 0.6mm by [34].Uniaxial tension tests and press-forming tests were carried out at various temperatures. The influences of anisotropy and temperature on deformation characteristics were investigated. Formability parameters such as average plastic strain ratio, planar anisotropy, and work hardening exponent were determined by tensile test results. Tensile test results indicated that the normal anisotropy parameter value of LZ61 was not large enough to give good drawability at room temperature. The large negative value of the normal anisotropy parameter would result in serious ear formation during drawing process at room temperature. The forming limit diagrams have been experimentally evaluated at various temperatures. The LZ61 Mg alloy presented reasonable ductility at room temperature, but this alloy did not exhibit good stretchability and drawability. Anisotropic behaviors were observed in the mechanical properties at all test temperatures. The tensile properties and formability parameters were correlated with the forming limit diagrams. Some improvement of the stretchability of LZ61 alloy could be made by deforming the sheet at a higher temperature due to an increase in the normal anisotropy parameter value with temperature, though *n* value 0.159 dropped with increasing temperature. Increase in the normal anisotropy parameter value and decrease in the normal anisotropy parameter value with increasing temperature revealed that the drawability of LZ61 alloy could be improved by forming the sheet at elevated temperatures. Drawability improved for sheet deforming at 200˚C, with the limiting fracture major strain about 25.22% and the limiting minor strain about 20.43% in tension–tension region, as shown in Fig. 7. In tension–compression region, the maximum major strain was about 43.35%, the minor strain around 24.75%.

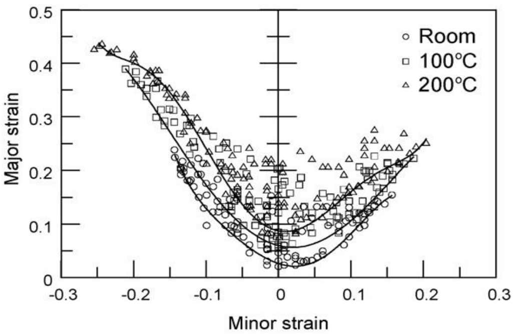
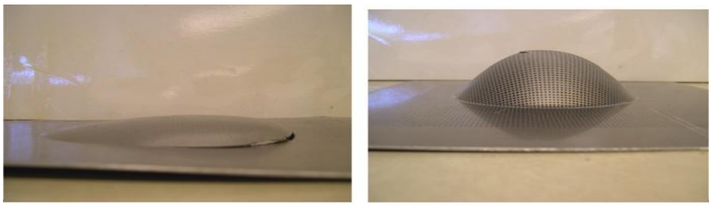


Fig. 7 Forming limit diagram of the LZ61 sheet at various temperatures.

In forming the Mg alloy AZ31-O, significant formability improvement was achieved at elevated temperatures compared to room temperature. Elevated temperature hydraulic bulge tests for Mg AZ31-O alloy sheets were conducted by [35] at the Institute for Production Engineering and Forming Machines (PtU), of Technische Unversitaet Darmstadt using a submerged tool, designed to minimize the temperature variation in the sheet. Experiments were conducted between room temperature and 225^{0}C, at various approximate true strain rates. Strains upto 0.7 were obtained at 225^{0}C and0.025 s^{-1}At higher temperatures and lower strain rates, thermal/work softening or stress dropped due to diffused necking . Bulge profiles at different bulge heights were measured using a CMM and the best radius values were calculated through least-square fit using several measured points. Residual plots were made to demonstrate the amount of deviation from a sphere with increasing bulge height. Twelve and 38mm bulge heights were obtained at room and elevated temperatures, respectively as shown in Fig.8.Measured and calculated bulge radius and thickness values were compared with the available analytical models and Amount of error that occurred in flow stress calculation by deploying the well-known membrane theory was investigated. Minimum thickness values were not always observed at the apex. Analytical models for thickness and radius calculations were found to be acceptable up to h_d/d_c ratios of 0.2 (h_d approx. 25 mm). At higher bulge heights (h_d>30), comparisons between measured, calculated thickness and bulge radius values showed a difference of 8% and 6% from experiments, respectively.



h_d=12 mm(Room Temp.) h_d=38 mm (225 C)

Fig.8.Variation in formability at room and elevated temperatures

In [36], warm formability of three sheet magnesium alloys AZ31, ZK10, and ZW41was measured under isothermal conditions using the Ohio State University test (OSU) formability test adapted for testing at elevated temperatures ranging from 150 to 350˚C and at a punch velocity of 1 mm/s. The punch and die were machined from D2 tool steel (ASTM A 681-08, 2007).The adapted test reliably enforced the plane strain tension over a significant fraction of the sample, thus providing an assessment of FLD(0), the minimum major strain value on a forming limit diagram. By mathematically modeling the strain as a function of punch displacement, a case was made that the punch displacement itself provided an expedient approach to ranking the relative formability of sheet metals. Combined with knowledge of the constitutive behavior of the material, the punch displacement strain relationship provided an explanation for the observed shape of the punch load versus displacement curves. Test results showed good formability at mildly elevated temperatures for the conventional magnesium alloys, AZ31 and ZK10, as well as superior formability of alloy ZW41, with an FLD(0) value of ~0.44 at 215˚C (~37% improvement over the conventional). An anomalous formability decrease lead to a formability minimum in all three alloys in the range of T=250˚C, due to the transition in failure mechanism from localized shear band-related plastic instability at low temperatures to more uniform necking at the highest temperatures.OSU formability test results showed that a new magnesium sheet alloy, yttrium-containing ZW41, was significantly more formable than traditional magnesium alloys AZ31 and ZK10. The improvement was linked to a more random texture in the new alloy, which diminished the tendency for gross, catastrophic shear instability.

The authors in [37] proposed an experimental methodology based on the Marciniak stretch forming test to investigate sheet formability of the Mg alloy AZ31 in warm conditions (200^0C), taking into account not only the temperature but also the strain rate effect. Specific tools to carry out such a formability test were designed and created: a flat punch of 92mm diameter (in line with Marciniak's test), embedded heating system was adopted in order to heat the central part of the specimen both rapidly and uniformly, where ruptures were forced due to the presence of a driving sheet between the specimen and the punch. A Digital Image Correlation system was also embedded in the formability equipment in order to acquire major and minor strains continuously and evaluated the moment and location of failures as in Fig.9. Finite Element simulations were run in order to define punch speed profiles (which differed according to the geometry of the specimen) that were able to keep a constant equivalent strain rate in the region where ruptures were forced. Experimental tests implementing the punch speed profiles were carried out in order to obtain temperature, load and strain data. FLCs at two different strain rate levels ($0.02s^{-1}$ and 0.002 s^{-}1) shifted upwards by about 35% at a temperature of 200^0C. The proposed approach for FLC evaluation was effective for materials whose properties were strongly influenced by the strain rate. Such FLC data could be usefully implemented in numerical simulations of sheet metal forming processes: while tensile tests were used to determine variations in mechanical behaviour according to the strain rate, both the stain rate sensitivity index and the maximum elongation increased in line with the temperature. The punch speed profile seemed to be effective in keeping the strain rate constant for almost the whole test, reasonably near to the target strain rate value. The FLCs evaluated in this work allow us to determine the occurrence of strain path-dependent critical conditions according to the strain rate.

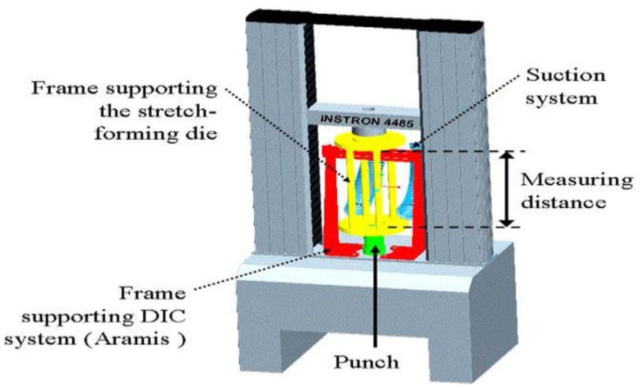


Fig. 9 Equipment for formability evaluation.

The sheet formability of AZ31 magnesium alloy has been widely investigated in [38] by means of uniaxial tensile and hemispherical punch tests, performed at different temperatures and strain rates, using samples with different fibre orientations on hydraulic testing machine by heating the samples, in the temperature range from 200 to 300°C, using a resistance furnace. Different samples keeping length constant (100mm) and the width were varied from 12.5 to 100mm.The results of the uniaxial tensile tests were analysed in terms of flow curves, ductility and micro structural evolution. They showed that the flow stress decreased, strain rate reduced and ductility, strain rate sensitivity coefficient increased with increase in temperature whilst the strain hardening exponent increased with increasing strain rate and decreasing temperature and the ductility was independent of the fibre orientation, slightly affecting the flow stress values. The constitutive behaviour and strain rate analysed has been described using the well-known Backofen-type equation: $\sigma = \varepsilon^{n} \dot{\varepsilon}^{m}$ where A, the strength coefficient, n the strain hardening exponent and m the strain rate sensitivity coefficient. Both m- and n-values were affected by the fibre orientation; The formability, described by the forming limit curves (FLCs), improved with increased temperature and decreasing strain rate with a more marked effect in the stretching side of the forming limit diagram; such behaviours were related to the micro structural evolution, that was strongly influenced by temperature and strain rate, due to the occurrence of grain boundary sliding, dynamic recrystallisation and grain growth. The formability along the rolling direction (RD) was higher than that along the transversal one (TD), even if the FLCs obtained along the TD had a larger extension in the drawing side than the ones along the RD. Such behaviours were related to the constitutive parameters and microstructure developed during deformation.

The authors in the study [39] focused on the improvement of formability of MgAZ31B alloy through friction stir processing. The friction stir processing was done on a vertical head milling machine, with the position of the tool fixed, relative to the surface of the sheet. A non-consumable taper threaded tool made of high carbon steel H13 with a shoulder diameter of 18 mm and a pin of diameter 6 mm and length 3 mm was used. Rectangular blanks of dimension 100 mm X 60 mm were used to conduct the LDH tests in plane-strain condition. Square specimens of size of 100 mm X 100 mm were blanked from the friction stir processed sheets for biaxial stretch forming. Specimens of size 140 mm long and 124 mm wide were used for Ohio State University test (OSU) test. All LDH tests were carried out in dry condition at a punch speed of 0.3 mm/s on a 50 ton hydraulic press. An optimum blank holding force in the range of 3–4 ton was applied. The processed samples were evaluated for elongation, strain hardening index, n, work hardening capacity, 1/YR and anisotropy, r. The formability of the processed samples was evaluated through two test methods namely the LDH test and Ohio State University test (OSU). The same trend of the formability behavior was found for all the samples tested irrespective of the different testing procedures followed. Further, it has been found that both rotational speed and traverse speed had significant effect on the formability. An inverse relationship existed between the yield strength and the LDH. It was found that, work hardening capacity, the inverse of yield ratio (YR), was an indicator of LDH value rather than the yield strength and uniform elongation. A statistical model has been developed to predict the formability characteristics. It was seen that, the friction stir processed material, has more FLD (0) values, and also higher than the base metal. FLD (0) was the lowest point in the FLD diagram. It was in the major strain region and measured at plane-strain condition. The FLD of the base metal and processed metal are shown in Fig. 10. The, developed model could replace the tedious formability testing procedures with a simple uniaxial tensile test, it was presumed that formability index, FI = (e X n X 1/YR)/r, FI was more for the samples with low r value, and thus, in the developed model, r was in the denominator .The results obtained from the developed model could be used as a basis for establishing the optimal friction stir process parameters, to develop the desired formability properties in Mg AZ31 alloy.

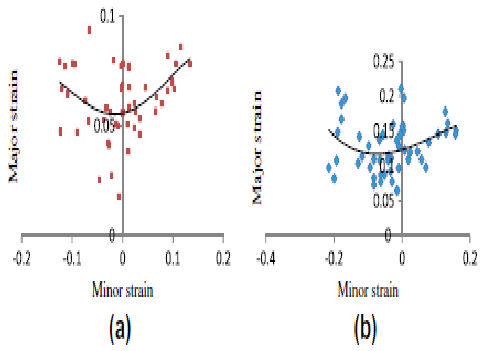


Fig.10 Forming Limits of (a) base sample (b) FSP sample

Formability of four magnesium AZ31B sheet materials, produced either by direct chill or twin roll continuous casting, was investigated by [40] at 400°C and 5×10−3s−1 using pneumatic stretching. Sheet specimens were deformed through a series of four elliptical die inserts, with aspect ratios ranging between 1.0 and 0.4, producing ellipsoidal domes with different biaxial strain combinations. Testing was carried out in two scenarios, i.e. with the major strains aligned either along or across the rolling direction of the material. Circle grid analysis was then used to map the planar strains of the deformed specimens; the latter were used to generate comprehensive material forming limits curves (FLCs) that bound the safe, marginal and failure deformation zones. For all four sheets, the 0° orientation showed greater formability limits than the 90° orientation. This was further confirmed through dome height measurements. Orientation effects were quantified by constructing a "composite FLD" for each of the four sheets; the diagrams collectively showed that greater formability limits were achieved along the material's rolling direction, when the major strains accumulated along the rolling direction, and are larger than the minor strains. Detailed comparisons between the four sheets were carried out based on formability limits, deformation uniformity and maximum dome height prior to failure and fracture surface morphology and chemistry. By comparing the formability results obtained for the four sheets, it was found that the sheets produced by TRC casting outperformed the one produced by DC casting mainly due to the finer grain size of the former compared to the latter .Disparities in formability were linked to differences in grain structure and material inhomogeneities. Formability limits reduced and premature failure was due to internal material defects in the form of long oxide stringers. TRC cast sheets were more prone to this kind of defects.

III. Conclusion

The main objective of the present study is that of extending and improving research into the combined effect of strain rate and temperature on material formability. Formability test results showed that a new magnesium sheet alloy, yttrium-containing ZW41, was significantly more formable than traditional magnesium alloys AZ31 and ZK10. The improvement was linked to a more random texture in the new alloy, which diminished the tendency for gross, catastrophic shear instability. The formability of Magnesium alloys increased at elevated temperatures depending on the thickness and the forming process adopted. A brief review of formability of Magnesium alloys at elevated temperatures presented here would serve as platform for further development in light-weight metals and alloys and helpful in meeting the great demand for enhancement of fuel efficiency and dynamic performance of structural components in the aerospace, electronics, and automobile industry to replace some existing materials.

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