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Technical Report

Modelling studies of sheet metal formability of friction stir processed Mg AZ31B alloy under stretch forming

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ABSTRACT

Magnesium alloys have poor formability at room temperature. The formability can be improved through hot forming at the cost of deterioration in strength and other mechanical properties. Improvements in texture and grain refinement are the alternate ways for formability improvement. The economically viable process for such applications is alloying or grain refinement technologies like equal channel angular pressing (ECAP), friction stir processing (FSP), and accumulative roll bonding (ARB), etc. Friction stir processing is an emerging solid state microstructure modification technique that can produce homogeneous microstructure with fine-grains in a single pass. The desirable characteristics for sheet formability are the maximum limiting dome height under plane and biaxial strain deformation conditions and the major fracture strain limits through forming limit diagrams (FLDs). Equiaxed homogeneous microstructure with fine grains through FSP results in the enhancement of formability of the material. The objective of the present work is to establish the methodology for viable sheet metal forming practices by altering the process conditions. This needs a clear understanding of the friction stir processed Mg alloy under different strain conditions to get optimized process parameters.

1. Introduction

Mg alloys exhibit poor ductility and formability because of limited active slip systems in basal planes. Many research papers provide information regarding formability improvement in Mg alloys through fine grained structures [1–3]. Dynamic recovery induced by plastic compatibility stress and activation of non-basal dislocation slip systems improve formability [4]. Dynamic recovery at room temperature is associated with small angle grain boundaries and formation of twins. This can improve formability limits that may enhance deformation of complex bodies [5]. Researchers are involved in developing effective and efficient methodologies, for microstructure modification, to provide severe plastic deformation along with higher strain rates, than the conventional methods like ECAP, HPT and ARB [6,7]. The industry needs process automation to meet the present day global needs. Modelling is one such technique for the development of automatic systems for mass production. The formability studies adopt various formability tests like the limiting dome height (LDH) and Ohio State University (OSU) test to investigate the stretchability of friction stir processed samples. Karthikeyan et al. [8,9] studied the influence of friction stir processing process variables namely the rotational speed, the traverse speed and the axial force on the mechanical properties of the aluminum alloys such as AA6063-T6 and cast A319. They obtained maximum mechanical properties for certain combination of parameters by optimizing the process. El-Danaf et al. [10] carried out the friction stir processing of commercial AA 5083 rolled plates with a tool rotational speed of 430 rpm and a traverse feed rate of 90 mm/min. They obtained a fine grained microstructure of size 1.6 μm and an average misorientation angle of 24°. They measured the ductility using tensile tests at a temperature of 250 °C at three strain rates, and demonstrated that the enhanced ductility and lower forming loads are due to the decrease in the grain size. Lee et al. [11] developed an internal variable approach to high temperature deformation and super plasticity of Mg alloys through a series of load relaxation tests at room and elevated temperatures. They established different types of deformation mechanisms for different Mg alloys at different processing conditions. They established the possibility of super plasticity behavior of AZ31 alloys and studied temperature and grain size effect, to understand the material behavior under different process conditions. The load relaxation test when combined with an internal variable theory provides a powerful means to characterize the dominant deformation mechanisms. AZ31 Mg alloy undergoes grain boundary sliding (GBS) and grain matrix deformation (GMD) during the process. Internal variable approach provides kinetics relations for the deformation rate variables. Park et al. [12] attacked the problem of creep behavior through internal variable approach for Mg alloys. The creep behavior under elevated service conditions can be described by two deformation modes namely the dislocations glide and the

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dislocations creep by the internal variable theory. Activation of dislocations from basal to prismatic planes above 523 K is one such technique to understand the creep behavior that affects the super plasticity of Mg alloys. Kom et al. [13] developed a series of boss forming tests using AZ31 Mg alloy sheet at elevated temperature with various lubrication conditions to obtain the optimum processing condition. They proposed a methodology for reduction of surface defects during boss forming. The strain concentration in the mid part of a boss is considered to be the main cause of shrinkage cavity formation. Lubrication on the front side reduces the damage formation while a higher frictional coefficient reduces formation of shrinkage cavities. Kim et al. [14] established grain size effect on the dome forming limit and deformation mechanism of AZ31B Mg alloy sheets. They further developed a methodology to understand the deformation mechanism of biaxial test results using deformation behavior of simple uniaxial results. The stretchability of rolled sheets was high with larger anisotropy (r), higher n values and lower yield stress. Darras et al. [15,16] have studied the effect of various friction stir processing parameters on the thermal histories and properties of commercial AZ31B-H24 magnesium alloy sheet. They concluded that the grain refinement and homogenization of microstructure can be achieved in a single pass.

The present work objective is to understand the Mg sheet-metal formability behavior under plane and biaxial stretch forming condition. It includes the development of a model for automatic control of process parameters for stretchability.

2. Experimental methodology

The as-received material was AZ31B magnesium alloy with composition of (in wt.%): Al – 3.02, Zn – 0.89, Mn – 0.29, Si – 0.026, Ni – .0009, Fe – 0.0025, Mg-balance. The magnesium sheet was cut into the required size by milling machine. 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. The FSP setup is shown in Fig. 1. The work piece was firmly clamped to the bed and a specially made tool was plunged into the selected area of the material sheet, for sufficient time, in order to plasticize the material around the pin. After adequate plasticization, the tool was traversed across the surface of the material for a single pass. The entire sheet was processed with overlapped passes. 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. The FSP experiments were conducted on the sheet in the rolling direction as per the selected orthogonal array as shown in Table 1.

Mechanical properties of friction stir processed sheet were evaluated by carrying out tensile tests on universal testing machine. The specimens were prepared as per the ASTM E8 M-04 guidelines. Three specimens were tested and the average results are presented in Table 1.

Fig. 1. Friction stir processing setup.

Limiting dome height (LDH) test and the Ohio State University (OSU) test were used to investigate the stretchability of friction stir processed samples. These tests are designed to simulate stretching, in plane-strain, with minimal bending strain. The LDH test can also be used to impose biaxial stretching on a sheet specimen, which is referred to as a full-dome test. The OSU test has promising improvement in the scatter and speed compared to LDH method because a critical-width finding procedure is not required to obtain the plane-strain condition. In this work, the formability in plane strain and biaxial stretch forming condition were determined using LDH and the plane strain formability using OSU test. Trial experiments were carried out to determine the plane strain condition by varying the sample width. It was found that a near plane strain condition could be achieved with a sample width of 60 mm. So, rectangular blanks of dimension 100 mm $\times$ 60 mm were used to conduct the LDH tests in plane-strain condition. Square specimens of size of 100 mm $\times$ 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 OSU test. All the samples were marked with 2.5 mm diameter grid circles to measure the forming limits after deformation. Circular lock beds were designed on the dies to restrict the flow of material from the flange region to the die. All LDH tests were carried out in dry condition at a punch speed of 0.3 mm/s on a 50 ton hydraulic press. The hydraulic press with the LDH toolset is shown in Fig. 2a. An optimum blank holding force in the range of 3–4 ton was applied. The punch was stopped immediately after the onset of fracture of the specimen during the tests. The load–displacement data of the specimens were recorded and stored using data loggers. In order to determine the minor and major strains, the minor and major diameters of the deformed circles (ellipses) were measured by a tool maker's microscope. The results of formability test of the specimens are presented in Table 2 along with the results of other formability tests including major fracture strain limits. The deformed specimens after forming are shown in Fig. 2b.

3. Results and discussion

3.1. Tensile properties

It can be observed from Table 1, that the process parameters, tool rotational speed (TRS), tool traverse speed (TTS) and tilt angle play a greater role during friction stir processing of magnesium alloys. From the experimental results, it is seen that, as the rotational speed increases, the tensile strength and the percentage elongation increases. This is due to the refinement of grain by the increased heat input. At a lower rotational speed (900 rpm), the mechanical properties were found to be lower because the heat required for softening the metal has not reached, for it to go to the plasticized state. As the rotational speed is increased above 1150 rpm, the tensile strength decreased. Because of higher rotational speeds (1400 rpm), excessive grain growth was experienced, due to the increase in the temperature, which subsequently leading to lower tensile properties. This increase in grain size with increase in the rotational speed is in accordance with the results published by Chang et al. [7]. According to the results obtained, it is evident that, as the traverse speed increases, the tensile strength and the percentage of elongation increases and then it decreases due to non-availability of sufficient time for plasticization.

Higher traverse speed produces poor plastic flow of the material due to the poor disintegration of the metal at the tool interface. Variation in the mechanical properties was also experienced due to the change in the tool tilt angle. A tool tilt angle of 0° caused a serious problem of decreased tensile strength at lower rotational speed. An increase in the tool tilt angle resulted in an inclined force

Table 1
Taguchi's L_9 standard orthogonal array with responses.

TRS (rpm)	TTS (mm/min)	TA (°)	YS (MPa)	TS (MPa)	*e* (%)	*n*	*r*	1/YR
900	24	0	150	195	5.5	0.2295	0.598	1.300
900	32	1	178	239	8.2	0.2632	0.384	1.342
900	40	2	165	220	7.8	0.2382	0.608	1.333
1150	24	1	174	234	9.3	0.2814	0.492	1.345
1150	32	2	175	240	10.0	0.2934	0.398	1.371
1150	40	0	168	225	7.6	0.2631	0.532	1.357
1400	24	2	136	180	7.9	0.2311	0.565	1.324
1400	32	0	143	197	9.95	0.2963	0.369	1.377
1400	40	1	132	180	8.1	0.2390	0.53	1.343
	Base metal		163	210	6.97	0.2260	0.607	1.288

Fig. 2a. Hydraulic press with die set.

acting on the metal, resulting in the homogenization of material flow, and thereby giving better mechanical properties.

3.2. Formability

Formability of the friction stir processed samples and base metal was studied in terms of the results obtained by formability tests such as limiting dome height obtained in plane-strain condition, biaxial condition, punch height before failure (PHF, OSU), fracture limits and fundamental material parameters such as work hardening exponent (*n*), anisotropy (*r*) and work hardening capacity (1/YR). It is seen from Table 2 that both rotational speed and traverse speed have significant effect on formability. At lower rotational speed (900 rpm), the amount of heat generation for softening the material is not sufficient for complete deformation resulting in less formability. With increased rotational speed, formability has been improved due to more grain refinement. The highest formability was obtained at a tool rotational speed of 1400 rpm, a traverse speed of 32 mm/min and a tool tilt angle of 0°. However, the tensile strength was poor (197 N/mm^2) because of higher temperature and lower strain. At lower (24 mm/min) and higher traverse (40 mm/min) speeds, less formability is observed because of poor plastic flow of the material due to increased frictional heat and insufficient heat generation. However, in this case the formability was found to be more than the parent material, because of grain refinement. The minor and major limit strains were determined at the plane-strain condition. It is seen that, the friction stir processed material, has more FLD(0) values, and also higher than the base metal. FLD(0) is the lowest point in the FLD diagram. It is in the major strain region and measured at plane-strain condition. The FLD of the base metal and processed metal are shown in Fig. 3.

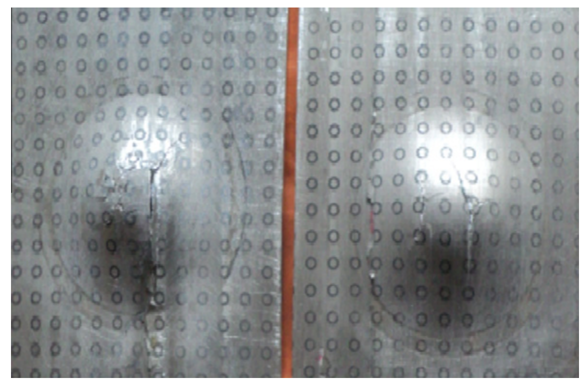

Fig. 2b. Deformed specimens.

Table 2
Formability results.

Sample no.	LDH_0 (plane strain, mm)	LDH (biaxial, mm)	PHF (OSU, mm)	Major fracture strain limit	FI
1	6.5	6.6	7.1	0.078	2.74
2	8.1	9.1	9.7	0.123	7.54
3	7.4	7.6	7.8	0.094	3.8
4	8.5	8.6	9.2	0.108	5.1
5	8.9	9.3	9.8	0.134	10.12
6	8.2	8.8	9.5	0.105	7.15
7	7.5	7.9	8.2	0.098	4.27
8	9.2	10.1	10.7	0.143	11.1
9	7.9	8.5	8.9	0.103	4.9

There is an inverse relationship between the yield strength and LDH. The LDH value generally increases with uniform elongation. Thus, the degree of change in LDH value is a function of yield strength and uniform elongation, whose values might be depending on the alloying system. Work hardening capacity which is the inverse of yield ratio (YR) is an indicator of LDH value rather than the yield strength and uniform elongation [17]. LDH value may be correlated with work hardening exponent which is needed to achieve large stretch formability at room temperature. Further structural changes have to be investigated for any observed unusual behavior during formability investigations.

Figs. 4a and 4b show the microstructures of the base metal and the processed metal. It indicates that a decrease in the grain size is favorable for the increase in the percentage of elongation while an increase in the grain size after deformation due to dynamic recovery favors improvement in the stretch formability. As observed in Figs. 5a and 5b, due to shear deformation in AZ31 sheet, the basal texture intensity has been reduced, resulting in improved stretch formability.

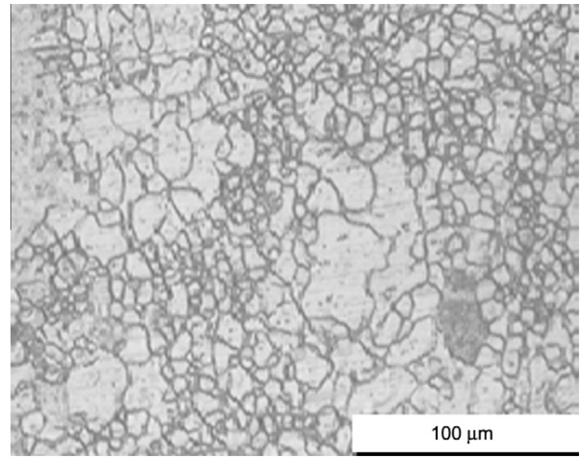

Fig. 4a. Optical microstructure of base metal.

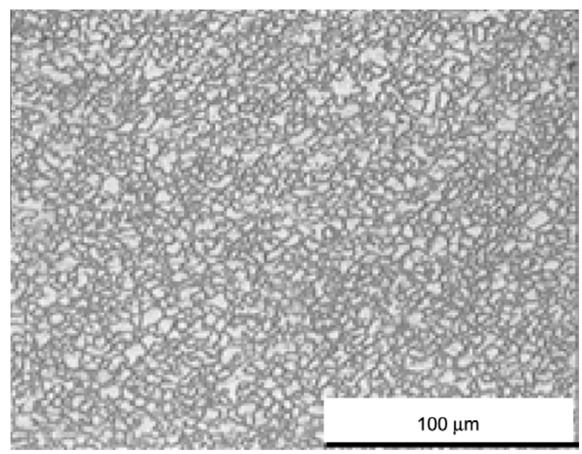

Fig. 4b. Optical microstructure of FSPed sample.

3.3. Tensile test as a measure of formability

The test results shown in Table 3 reveal that the uniform elongation provides the best fit for LDH at room temperature. The best fit relation is given by LDH = $0.262e_u + 0.133$. However, when LDH data is plotted against strain hardening component value, the relationship between the two is given by LDH = $34.33\ n - 0.982$. Relationships between LDH and uniform elongation, work hardening components and work hardening capacity are shown in Figs. 6–8. Figs. 6 and 7 indicate linear relationship between LDH and uniform elongation and work hardening component and LDH respectively. Thus, there is a proportional relationship between the uniform elongation and the work hardening component. Hence, large work hardening component is needed to have better stretchability. The results indicate that, the room temperature formability of Mg alloys can be improved by increasing the work hardening component that can be achieved by controlling microstructural features. Fig. 8 indicates a linear relationship between the LDH and the work hardening capacity. The LDH value increases with increase in the work hardening capacity.

Generally, a difference in LDH of 0.5 mm represents the difference between acceptable and unacceptable performance in the press. From Table 3, it is clear that the total elongation provides a less reliable estimate of stretch forming than the LDH test as error is greater than 0.5 mm which is generally considered to be tolerable for LDH. However, the errors with hardening capacity and anisotropy ratio are not at all reliable estimates for stretch formability. Straining in the thickness direction is required for improved in the stretch formability to promote biaxial tension mode which is not taken care in uniaxial tension test.

3.4. Model for stretch formability

Table 2 indicates limiting dome height values in the plane strain stretching, biaxial stretching and OSU plane strain stretching. It is clear from Table 2 that though the numerical values are differing in all the three tests, the trend is same. Similarly limiting strain values obtained from FLD diagram has the same trend as that of LDH. The intention of this work is to develop a model for plane stretching and biaxial stretching from the responses of uniaxial test results. The developed model is expected to correlate the trend behavior of all the four responses.

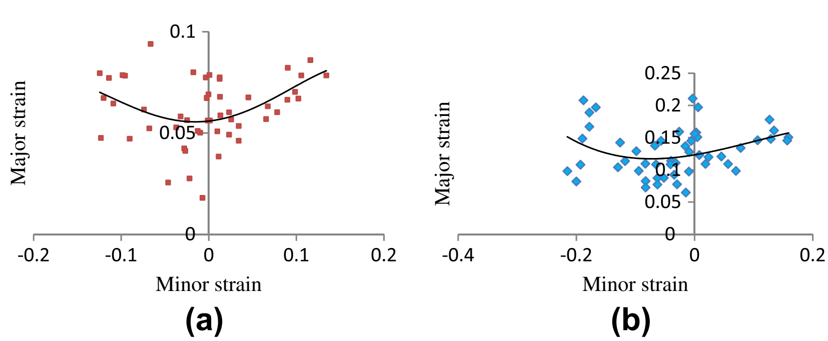

Fig. 3. Forming limits of: (a) base sample and (b) FSPed sample.

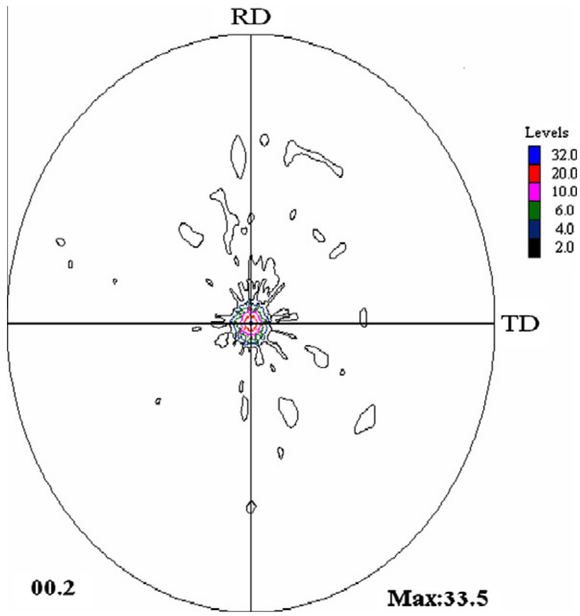

Fig. 5a. Pole figure of as received material.

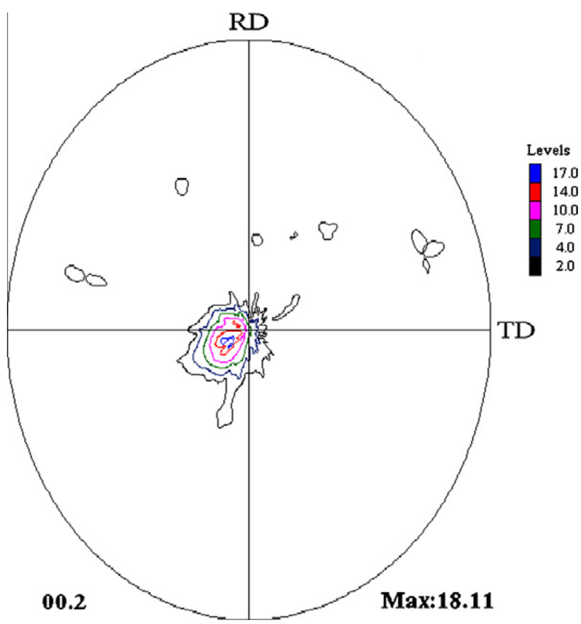

Fig. 5b. Pole figure of FSPed material.

Table 3
Slopes and intercepts for best-fit linear curves relating LDH, e_u and 1/YR.

Fit	Intercept	Slope (mm/pct)	Standard error of estimate (mm)
e_u vs. LDH	0.133	0.262	0.8763
n vs. LDH	−0.982	34.33	0.9731
1/YR vs. LDH	35.79	32.61	2.62

The literature [18] indicates that the formability of any material is a function of elongation (e), work hardening component (n), anisotropy (r) and work hardening capacity (1/YR), which has been confirmed by our work, as the formability obtained in the experiments conducted is a function of all the stated above.

Hence, it is presumed that formability index,

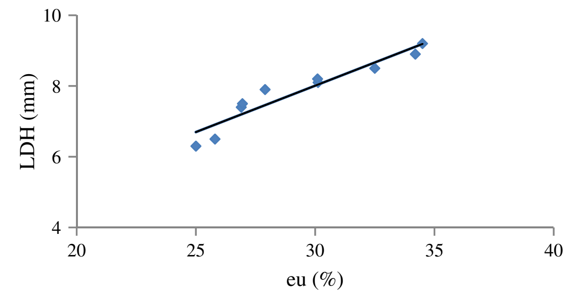

Fig. 6. Variation of LDH with e_u.

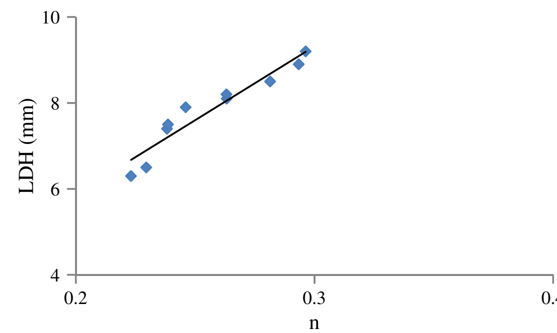

Fig. 7. Variation of LDH with n.

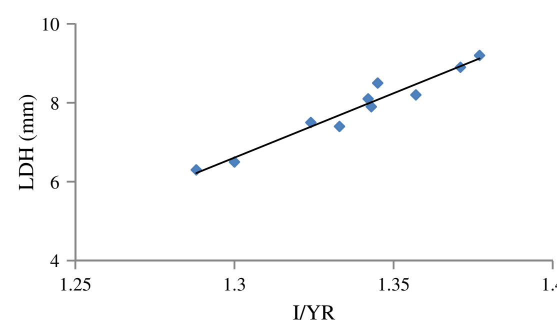

Fig. 8. Variation of LDH with 1/YR.

$$FI = (e \times n \times 1/\mathrm{YR})/r. \quad (1)$$

The experimental values obtained from Table 1 were substituted into Eq. (1) and the obtained FI values are shown in Table 2. It is observed that the trend of FI is similar to the trend of the four formability parameters mentioned above. Hence, the optimized parameters for uniaxial testing can be directly used as the optimized parameters for the FI. This eliminates the laborious tests to be conducted for formability.

For improved drawability, higher r value is useful. However, for stretch forming, this may not be true. However, it cannot be correlated fully, due to strong basal texture of magnesium alloys.

The biaxial formability has been reported to depend both on r and n values together with the yield stress [13]. Twinning and basal slip are the major deformation mechanisms at low temperatures, together with some non-basal slips caused by stress concentrations. The stretchability of AZ31 is very limited when compared with conventional sheet metals like aluminum alloys due to strong anisotropic deformation and r values. Hence, most of the structural materials like steel and aluminum alloy emphasize high r values for better stretchability. However, this is not true with Mg alloys which may require low r values for better stretchability. This is observed from Table 2 that the formability index, FI is more for the samples with low *r* value, and thus, in the developed model, *r* is in the denominator.

The designers should be cautious while selecting the material and the process parameters for highly stretchable products, as low yield stress and low *r* values are the desired properties for this particular application. This may limit the tensile strength of the material and may need higher thicknesses of the product to withstand larger stresses that may arise during service conditions. It may be possible to tide over the problem through improvement in strain hardening exponent and strain hardening capacity by suitable means so that these higher values may counter act the effect of low yield stress and high *r* values.

4. Conclusions

This study has focused on the improvement of formability of Mg AZ31B alloy through friction stir processing. 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 OSU test. 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 have significant effect on the formability. An inverse relationship exists between the yield strength and the LDH was found. It was found that, work hardening capacity, which is the inverse of yield ratio (YR), is an indicator of LDH value rather than the yield strength and uniform elongation. From the conclusions drawn above, a statistical model has been developed to predict the formability characteristics. The developed model can replace the tedious formability testing procedures with a simple uniaxial tensile test. The results obtained from the developed model can be used as a basis for establishing the optimal friction stir process parameters, to develop the desired formability properties in Mg AZ31 alloy.

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