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INFLUENCE OF SETTING VARIABLES IN CONVENTIONAL SUPER PLASTIC FORMING PROCESS USING GREY RELATION ANALYSIS IN TAGUCHI METHOD

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ABSTRACT

Super plastic forming (SPF) is a manufacturing process utilized in the automotive industry to produce complex geometry aluminium or magnesium alloy components which cannot be fabricated at room temperature. During the SPF, the process parameters such as die entry radius, pressure, temperature and Material Thickness at the sheet die interface greatly influence the metal flow. The aim of the present work is to design and fabricate a set of punch and die to, produce a hemispherical cup out of AA2024 sheet in order to study the these process parameters. The sheet is placed in a die, which can have a simple to complex geometry, representative of the final part to be produced. It is shaped into the hemispherical cup using compressed air. These input parameters were varied and output parameters such as thickness variations, maximum height, Diameter and minimum forming time of cup were studied and L9 orthogonal array .In order to obtain the output parameters affecting product quality, both Grey relational Analysis and ANNOVA were evaluated.

Keywords: conventional super plastic forming, grey relation analysis.

INTRODUCTION

SPF is a technique of presswork high temperature of metal sheets that falls in hot blow forming processes. The elongation obtained with this technology exceeds 100% and limits on obtainable forms in a unique forming process are very low. The mechanical characteristics of the finished product are very good, because the hardening of material is practically absent and spring-back is zero, with benefit of obtained dimensional accuracy. The surface finish is excellent, so there is no need to make finish operations. Furthermore, light alloys can be formed with this technology without problems of obtainable geometries. Indeed, in the aerospace industry, the super plastic forming has been used for thirty years. On the other hand, the forming process is very costly: the working temperatures are very high (approximately 60% of melting temperature), the average size of grains must be less than 10 µm and the strain rates must be less than 10^{-2} s^{-1}. Materials with small size of grains are costly because they require very expensive treatment in terms of energy and time [1]. Furthermore, limited strain rates would make the lead times very long, therefore unacceptable in modern industrial mass productions [2, 3]. To assess the possibility of making a component with SPF technology, it is necessary to take into account both technological and economic factors. Numerous works have been separately studied some of these factors with numerical simulations or with experiments. For example: Naka and others have studied, with physical tests, the effects of temperature and forming speed on the forming limit diagram for type 5083 aluminum alloy sheet [4]. Whereas Taleff and the others have simulated bulge forming experiments on Material s with two different fine grained AA5083 sheet materials at two temperatures and they have studied the rupture limit and the forming time [5]. Luckey and the others have simulated and validated a two stage SPF, showing how the thickness profile improves at this technology [6]. A preliminary estimate of “performance” of a super plastic forming process, help to decide if this type of technology is the best suited to the needs, both of project that of market, while optimising the process is fundamental in the modern industry. Many research papers suggest SPF process evaluations, but proposed considerations are difficult to compare because of deeply different methods, case studies and results used in each simulation or experimentation. In this paper, starting from a careful analysis on super plasticity phenomenology and process, a set of indexes is proposed to evaluate performances of SPF on a product. These indexes can be evaluated by numerical simulations and must be statistically combined. In particular we emphasize analysis of the influence of process variables by indexes on the most important production requirements. The parameters to be monitored during a SPF process depend on the physical phenomena that underlie this technology. They are the grain boundary sliding (GBS), the dislocation creep (DC) and the grain boundary diffusion (GBD) [7-9]. The relative weight of each phenomenon, still being an object of study, depends on the average size of grains, the processing temperature, the strain rate and the processing pressure. With GBS phenomenon, the grains, under certain conditions of temperature and pressure, taking a shape less hard-edged that allows the relative sliding [10-12]. This is macroscopically highlighted with great plastic deformations. This phenomenon manifested appreciably only if the average size of grains is less than 10 µm. With the mechanism of DC there is a dislocation movement of the lattice of metallic material [13]. This gives rise to plastic deformations of the lattice and consequently of all material. The Backofen formula, that is the most commonly used equation in Finite Element simulations of super plastic forming, join equivalent stress to strain rate

[15, 16]:$\sigma = K\dot{\varepsilon}^{m}\varepsilon^{n}$,K constant m strain rate sensitivity coefficient n coefficient the m coefficient increases with a strain rate up to maximum. This coefficient supplies information about thickness distribution on formed Material because it represents also the elongation capacity of material [17-20].

Table-1. Control factors and their levels used for Superplastic forming.

Parameters	Unit	Levels		
		1	2	3
Temperature	°C	125	250	375
Pressure	Bar	3	4.5	6
Die radius	mm	3	4	5
Material Thickness	mm	1	1.5	2

Experimental setup

Punch and die were designed and fabricated as per the requirement of SPF. Table-1 shows the process parameters under forming conditions. The sheet metal forming procedure with reference to different temperatures is also explained and is as follows.

Design of dies

The die design and fabrication is critical to gives passage for pressurized air to enter and forms the sheet metal into desired shape. Figure-1 shows the punch and die setup. The hole at the centre of the helps to send the compressed air, which falls on the sheet metal. The punch also helps to form the desired shape of the cup.

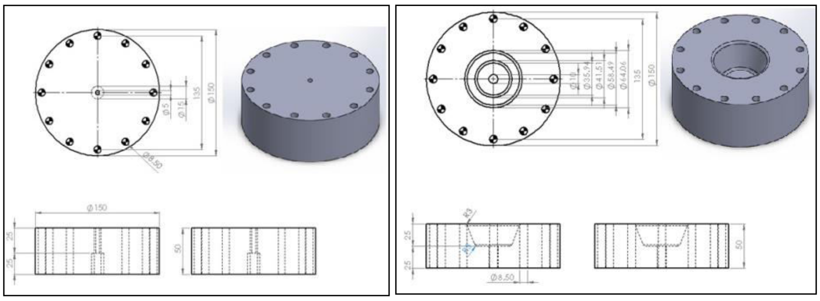

Figure-1. Top, isometric, front, top view of punch & die setup.

Specimen preparation and assembly of dies with sheet metal

Figure-2. Aluminium sheet specimen & assembly of dies with sheet metal.

The Figure-2 shows the assembly of dies with sheet. The sheet is placed in between punch and die. The sheet has required diameter holes in order to align holes of punch and die. The punch and die are placed at the bottom and top respectively as shown in Figure-3. The die is connected to a hydraulic pipe. The punch is placed on the burner, so direct heat is supplied. All the fasteners are fixed tightly in order to prevent any air leakage.

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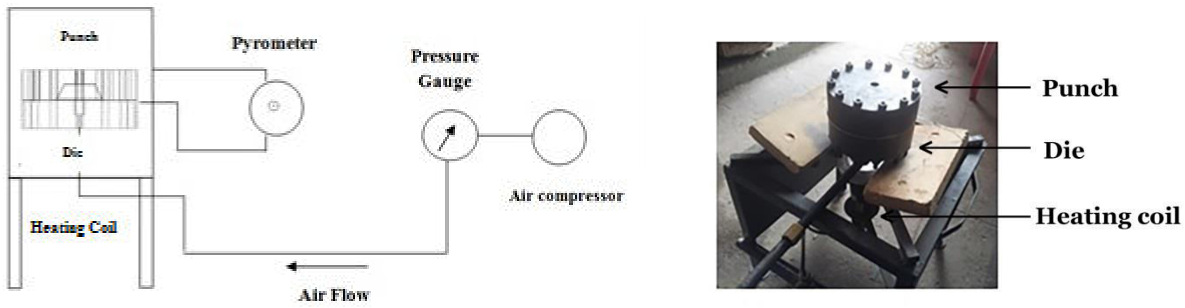

Figure-3. Schematic diagram of experimental setup.

The schematic diagram is shown in Figure-3, the experimental set up details are given below. Heating coil is used to cover the dies which are placed on the burner. The heating coilhelps to restrict the fire and allows it to heat dies at maximum extent. The dies are used to form the sheet to required shape to allow the pressurized gas exactly fall on sheet metal at the time of forming. The burner is used to heat the dies and sheet metal up to the required temperature. Pyrometer is used to know the surface and internal temperatures of die and sheet metal. Probes are used to detect the temperature on the surface and inside the dies. Compressor is used to send the pressurized air at time of forming. Pressure gauge is used to know about the amount of air allowed at the time forming. The dies are used to form the sheet to required shape and to allow the pressurized gas exactly fall on sheet metal at the time of forming. The burner is used to heat the dies and sheet metal up to the required temperature. Maximum diameter of the cup was determined by Machine Vision of Hexagon metrology, OLM 3020 based on the principle i.e. first optically enlarge parts and grabbed its photos by CCD Camera then transferring to computer, at last analysing and processing by means of measuring Software. Maximum height was found by for Formed Cup height by Profile Projector. Forming time was found by Stop Watch. Maximum thinning was found ultrasonic thickness gauge based on the principleie behind to measure the thickness of a part by measuring the time sound travels from the transducer through the material to the back end of a part, and then measures the time of reflection back to the transducer. The gauge was used to calculate the thickness of the formed cup based on the velocity of sound.

Table-2. Control factors and response used in the experiment.

Trial no.	**Temperature** (°C)	**Pressure** (Bar)	**Die radius** (mm)	**Material thickness** (mm)	**Super plastic forming response**			
					Maximum thinning (Initial - Final) (mm)	**Maximum diameter** (mm)	**Maximum height** (mm)	**Forming time** (min)
1	125	3	3	1	0.7	45	16.2	21
2	125	4.5	4	1.5	1.25	48	18.2	19
3	125	6	5	2	1.82	52	23	15
4	250	3	3	1	0.74	48	18.7	18
5	250	4.5	4	1.5	1.29	51	21.6	14
6	250	6	5	2	1.85	56	23.4	12
7	375	3	3	1	0.79	51	19.8	16
8	375	4.5	4	1.5	1.31	54	22.7	11
9	375	6	5	2	1.91	58	24.6	9

Step 1: Grey relation generation

The first step of grey relation analysis is done by pre-processing of the output response data. It is performed for normalizing the data, which is shown in Table 2. Maximum thinning, diameter and height, higher the better performance characteristic is considered, and therefore, it is normalized in the range between 0 to 1 using the formula to avoid the effect of various units and to reduce the variability. The normalized output parameter for maximum thinning, diameter and height corresponding to the larger the better criterion is expressed as

$$X_i^*(k) = \frac{X_i^{(0)}(k) - minX_i^{(0)}(k)}{maxX_i^{(0)}(k) - minX_i^{(0)}(k)} \quad (1)$$

Similarly, the normalized output parameter for Ra corresponding to the smaller the better criterion is Expressed as

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$$X_i^*(k) = \frac{max\, X_i^{(0)}(k) - X_i^{(0)}(k)}{max X_i^{(0)}(k) - min X_i^{(0)}(k)} \quad (2)$$

Where, $X_i^*(k)$is the normalised value, is the maximum value of the sequence, is the desired sequence and is the minimum value of the sequence. $X_i^{(0)}(k)$Is the minimum value of the sequence?

Step 2: Grey relational coefficients

In the second step, the grey relation coefficient is calculated to express the correlation between the best and actual experimental results for the both the responses. Grey relation coefficient is given Table-2. The grey relational coefficient can be shown as follows:

$$\gamma\, x_0(k), x_i^* = \frac{\Delta_{min} - C\Delta_{max}}{\Delta_{oi}(k) + C\Delta_{max}} \quad (3)$$

$$\Delta_{oi}(k) = \| X_0(k) - X_i^*(k) \| \quad (4)$$

Δ_{min}= Smallest value of$\Delta_{oi}(k)$
Δ_{max}= largest value of $\Delta_{oi}(k)$

$\Delta_{oi}(k)$: Various value between $X_0(k), X_0(k)$denotes the sequences and $X_i^*(k)$ denotesthe comparability sequences. γ is distinguishing or identified coefficient. If all the process parameters have equal weightage, then it is set to be 0.5.

Step 3: Grey relational Grade

The third step of grey relation grade is to determine the average grey relational coefficient corresponding to each performance characteristics. The evaluation of the multi objective characteristic is based on the grey relation grade, which is shown in Table-2. If the grey relational grade has greater value, it indicates that concerned parameters combination is the optimum value. The grey relational grade is expressed as follows:

$$\tau_i = \frac{1}{n} \sum_{i=1}^{n} (\gamma(x_o(k), x_i^*(k))) \quad (5)$$

Where,τ_i the grey relational grade, where n is the number of process outcome. The higher grey relation grade represents that the corresponding experimental results are considered to be closer to the ideal normalised value.

RESULTS AND DISCUSSIONS

Experiments are performed on Conventional SPF using box behnken design method and experimental results are listed in Table-2. Table-3 shows the normalized value, grey relation co-efficient and grey relation grade for the response Maximum Thinning, Diameter, Height and Forming Time according the equations (1 to 7). Figure-4 shows the response of grey relation grade for multi-response characterization. From the Table-3, it is observed that the Trail No.1 has the highest grey relation grade. The higher grey relation grade has better multi response characteristics and therefore the combination of parameters. The Optimum parameters are T1, P1, DR2 and BT1 i.e. Maximum thinning (mm) of 0.7, Maximum Diameter (mm) of 45, Maximum Height (mm) of 16.2 and Forming Time (min) of 21 resulted in the optimal combinations of SPF process parameters for achieving Maximum thinning, Diameter, Height and Minimum forming Time together.

Table-3. Normalized values, grey relation coefficient and grey grades of responses.

Trail no.	Normalized S/N ratio SPF				Grey relation co efficient SPF				Grey relation grade	
	Maximum thinning (mm)	Maximum diameter (mm)	Maximum height (mm)	Forming time (min)	Maximum thinning (mm)	Maximum diameter (mm)	Maximum height (mm)	Forming time (min)	Grade	Rank
1	0	0.571428571	1	0.395833333	2.9994	0.010526316	0.111111111	0.004524887	0.781390608	1
2	0.816215481	0.642857143	0.2	0.625	0.483887	0.010989011	1	0.003484321	0.374589977	6
3	0.632362944	1	0.4	0	0.655308	0.014084507	0.333333333	0.009345794	0.253017907	8
4	0.483267583	0	0.2	0.513888889	0.919456	0.007874016	1	0.003921569	0.482812817	2
5	0.858998776	0.642857143	0.2	0.118055556	0.456121	0.010989011	1	0.007092199	0.368550589	5
6	0.999795946	0.928571429	1.2	0.277777778	0.383671	0.013333333	0.090909091	0.005347594	0.123315245	9
7	0.482995511	-0.178571429	0	0.083333333	0.920132	0.00729927	1	0.007633588	0.483766339	2
8	0.551353557	0.928571429	0.2	0.298611111	0.776518	0.013333333	1	0.005181347	0.448758193	4
9	0.483267583	0	0.4	1	0.919456	0.007874016	0.333333333	0.002531646	0.315798669	7

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Table-4. Contribution of process parameters for maximum thinning (mm).

ANOVA for maximum thinning (mm)						
Source of variation	**Sum of squares**	**DOF**	**Mean square**	**F**	**F table**	**Contribution %**
Temperature	0.0096	2	0.0048	24.06	4.2	0.51
Pressure	1.8711	2	0.9355	4677.72	4.2	99.46
Die Radius	0.0004	2	0.0002	0.89	4.2	0.02
Material Thickness	0.0002	2	0.0001	0.39	4.2	0.01
Error	0.002	9	0.000200	—		
Total	1.8812	17				

Table-5. Contribution of process parameters for maximum diameter (mm).

ANOVA for maximum diameter (mm)						
Source of variation	**Sum of squares**	**DOF**	**Mean square**	**F**	**F table**	**Contribution %**
Temperature	54.2222	2	27.1111	135555.56	4.2	39.80
Pressure	81.5556	2	40.7778	203888.89	4.2	59.87
Die Radius	0.2222	2	0.1111	555.56	4.2	0.16
Material Thickness	0.2222	2	0.1111	555.56	4.2	0.16
Error	0.002	9	0.000200	—		
Total	136.2222	17				

Table-6. Contribution of process parameters for maximum height (mm).

ANOVA for maximum height (mm)						
Source of variation	**Sum of squares**	**DOF**	**Mean square**	**F**	**F table**	**Contribution %**
Temperature	16.1489	2	8.0744	40372.22	4.2	25.43
Pressure	44.3089	2	22.1544	110772.22	4.2	69.77
Die Radius	1.4956	2	0.7478	3738.89	4.2	2.35
Material Thickness	1.5556	2	0.7778	3888.89	4.2	2.45
Error	0.002	9	0.000200	—		
Total	63.5089	17				

Table-7. Contribution of process parameters for Forming Time (min).

ANOVA for forming time (min)						
Source of variation	**Sum of squares**	**DOF**	**Mean square**	**F**	**F table**	**Contribution %**
Temperature	60.6667	2	30.3333	151666.67	4.2	48.92
Pressure	60.6667	2	30.3333	151666.67	4.2	48.92
Die Radius	0.6667	2	0.3333	1666.67	4.2	0.54
Material Thickness	2.0000	2	1.0000	5000.00	4.2	1.61
Error	0.002	9	0.000200	—		
Total	124.0000	17				

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Table-8. Contribution of process parameters for Grey Grade.

ANOVA for Grey Relation						
Source of variation	**Sum of squares**	**DOF**	**Mean square**	**F**	**F table**	**Contribution %**
Temperature	0.0728	2	0.0364	182.11	4.2	64.63
Pressure	0.0214	2	0.0107	53.55	4.2	19.00
Die Radius	0.0093	2	0.0047	23.30	4.2	8.27
Material Thickness	0.0091	2	0.0046	22.83	4.2	8.10
Error	0.002	9	0.000200	—		
Total	0.1127	17				

Analysis of variance (ANOVA) is carried out to determine whether the significant parameter affects the performance characteristics. The results of ANOVA for the all input parameter and grey relation grade of the Conventional Super plastic forming are listed in the Table 4-7. From Tables 4 to 7, it is observed that Pressure is found to be most important parameter that affects the multi response of Maximum thinning, Diameter, Height and Forming Time. In the case of Grey relation Grade, the most influence parameter Temperature is found with higher percentage (64.3 %) contribution, when compare to other three parameters such as Pressure (19.00 %), Die radius (8.27 %) and Material Thickness (8.10 %). This clearly shows that with Pressure is predominated major factor of achieving higher Maximum thinning, Diameter, Height and Forming Time together and temperature is predominated major factor of achieving Maximum thinning, Diameter, Height and Forming Time in Grey relation grade.

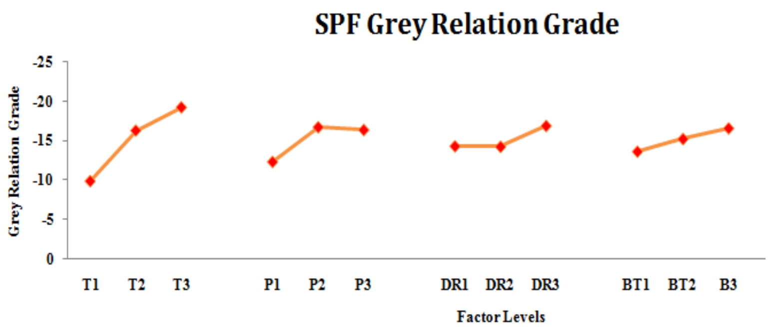

Figure-4. Main effect plots for grey relational grade.

Prediction of optimum conditions

Once the optimal levels of Conventional SPF process parameters are identified, the grey relational grade can be predicted using the following formula.

$$\gamma_{precdicted} = \gamma_m + \sum_{i=!}^{n} \gamma_i - \gamma_m \quad (6)$$

Where, predicted $\gamma_{precdicted}$ is the total mean of the grey relational grade, γ_m is the mean of the grey relational grade of optimal level and n is the number of Super Plastic Forming Process parameters that affects the multiple performance characteristics. The optimum value of SPF is predicted at the optimal levels of significant parameters, which has been identified as Temperature (T1), Pressure (P1), Die Radius (DR2) and Material Thickness (BT1) (Table-3 and Figure-4). The values of overall mean grey grade (γ_m) is taken as 0.5266, while the values for T1, P2, DR1 and BT2 are taken as 1.3795, 0.01177, 0.7037, and 0.01177 respectively (obtained from the Table 3). Substituting the above values in the equation 6, the γ predicted is found to be 0.4035.The confidence interval (95%) of the confirmation experiment is calculated by the formula given below.

$$C.I = \sqrt{F_\alpha(1, f_e)V_e\left(\frac{1}{\eta eff} + \frac{1}{R}\right)} \quad (7)$$

Where, $F_\alpha(1, f_e)$is the F ratio of the confidence level of (1-α) against DOF, fe is the error degree of freedom, R is the sample size of confirmation experiment (1),V_e is the error variance (0.002).The ηeff, is the effective number of replication is given as.

$$\eta eff = \frac{N}{1+(DOF\ associated\ in\ the\ estimate\ of\ mean\ response)} \quad (8)$$

Where, N =Total numbers of results = 9; where ηeff is .055. Where the F0.05 (1, 9) = 5.12 (taken from F Table [22]). Substituting these values in the various terms in the equations 7 and 8, the Confidence Interval (CI) isfound to be 0.238.

(GRG - CI) < GRG < (GRG + CI)
(0.781-0.238)< 0.781< (0.781 + 0.238)

Confirmation results

The confirmations tests for the optimal parameter with its levels were conducted to evaluate the quality characteristic for Conventional Super Plastic forming. The highest grey relational grade indicating the initial process parameters set of Temperature (T3), Pressure (P3), Die Radius (DR3) and Material Thickness (BT3) for the be multiple performance characteristics among the nine experiments. The predicted values are obtained by the equation 6. This ensures the usefulness of grey relation approach in relational analysis to achieve optimization where multiple quality criteria have to fulfil simultaneously.

CONCLUSIONS

The design and fabrication were quipped and the process parameters and experimental conditions were explained. The influence of the SPF process parameters such as Temperature, Pressure, Die radius and Material Thickness are analysed on the maximum thinning, Diameter, Height and Forming Time were studied by grey relation analysis and ANNOVA.

From this analysis, it is revealed that Temperature, Pressure, Die radius and Material Thickness are prominent factors which affect the SPF of AA2024.

a) Maximum Thinning. Temperature (0.51%), Pressure (99.46%), Die radius (.02%) and Material Thickness (.01%).

b) Maximum Diameter. Temperature (39.8%), Pressure (59.87%), Die radius (.16%) and Material Thickness (.16%).

c) Maximum Height. Temperature (25.43%), Pressure (69.77%), Die radius (2.35%) and Material Thickness (2.45%).

d) Forming Time. Temperature (48.92%), Pressure (48.92%), Die radius (0.54%) and Material Thickness (1.61%).

e) Grey Relation Grade. Temperature (64.63%), Pressure (19%), Die radius (8.27%) and Material Thickness (8.10%).

The best performance characteristics were obtained with SPF when Forming of AA 2024 Maximum Thinning, Diameter, and Forming Time with the T1 (125^0c), P1(3bar), DR2(4mm) and BT1(1mm). The best performance characteristics were obtained with SPF when Forming of AA 2024 Maximum Thinning, Diameter, Forming Time for Grey Relation Grade with the Maximum thinning (mm) of 0.7, Maximum Diameter (mm) of 45, Maximum Height (mm) of 16.2 and Forming Time (min) of resulted in the optimal combinations of SPF process parameters Confirmation test was carried out, using optimal levels, and the results were found to be better when compared to initial Forming conditions. The outcome of this study is useful for the manufacturing engineer to select the significant of Conventional SPF process parameters.

REFERENCES

[1] L.A. Dobrzanski, T. Tanski, L. cížek, J. Madejski. 2009. Selection of heat treatment condition of the Mg-Al-Zn alloys. Journal of Achievements in Materials and Manufacturing Engineering. 32: 203-210.

[2] S. Topolska. 2007. The role of quality control operations in a process of plastic forming, Journal of Achievements in Materials and Manufacturing Engineering. 23: 95-98.

[3] J. Majak, M. Pohlak, R. Küttner. 2007. A simple algorithm for formability analysis. Journal of Achievements in Materials and Manufacturing Engineering. 22: 57-60.

[4] T. Naka, G. Torikai, R. Hino, F. Yoshida. 2001. The effects of temperature and forming speed on the forming limit diagram for type 5083 aluminum. Magnesium alloy sheet. Journal of Materials Technology. 113: 648-653.

[5] E.M. Taleff, L.G. Hector Jr., J.R. Bradley, R. Verma, P.E. Krajewski. 2009. The effects of stress state on high temperature deformation of fine grained aluminum magnesium alloy 5083 sheet, ActaMaterialia. 57: 2812-2822.

[6] G. Luckey Jr., P. Friedmana, K. Weinmannb. 2009. Design and experimental validation of a two-stage superplastic forming die. Journal of Materials Processing Technology. 209: 2152-2160.

[7] L. Clarisse, A. Bataille, Y. Pennec, J. Crampon, R. Duclos. 1999. Investigation of grain boundary sliding during superplastic deformation of a fine-grained alumina by atomic force microscopy. Ceramics International. 25: 389-394.

[8] Yu. R. Kolobov, I.V. Ratochka. 2005. Grain boundary diffusion and plasticity/Super plasticity of polycrystalline and nanostructured metals and alloys. Materials Science and Engineering A. 410-411: 468-471.

[9] O.A. Kaibyshev, A.I. Pshenichniuk, V. Astanin. 1998. Superplasticity resulting from cooperative grain boundary sliding, Acta Materialia. 46: 4911-4916.

[10] J.A. del Valle, M.T. Perez-Prado, O.A. Ruano. 2007. Symbiosis between grain boundary sliding and slip creep to obtain high-strain-rate Superplasticity in aluminum alloys. Journal of the European Ceramic Society. 27: 3385-3390.

[11] N. Du, A.F. Bower, P.E. Krajewski, E.M. Taleff. 2008. The influence of a threshold stress for grain boundary sliding on constitutive response of polycrystalline Al during high temperature deformation. Materials Science and Engineering A. 494: 86-91.

[12] Y. Benveniste. 1997. Thermal expansion of polycrystals with grain boundary sliding. International Journal of Solids and Structures. 34: 789-798.

[13] B.N. Kim, K. Hiraga. 2000. Contribution of grain boundary sliding in diffusional creep, Scripta Materialia. 42: 451-456.

[14] L. Cížek, M. Greger, L.A. Dobrzanski, I. Juricka, R. Kocich, L. Pawlica, T. Tanski. 2009. Structure and properties of alloys of the Mg-Al-Zn system, Journal of Achievements in Materials and Manufacturing Engineering. 32: 179-187.

[15] A. Benallal, T. Berstad, T. Børvik, O.S. Hopperstad, I. Koutiri, R. Nogueira de Codes. 2008. An experimental and numerical investigation of the behaviour of AA5083 aluminium alloy in presence of the Portevin-Le Chatelier effect, International Journal of Plasticity. 24: 1916-1945.

[16] G. Giuliano. 2008. Constitutive equation for superplastic Ti-6Al-4V alloy, Materials and Design. 29: 1330-1333.

[17] F. Abu-Farha, R. Curtis. 2008. On the standard test methods for evaluating the tensile properties of metallic superplastic sheets, Proceedings of the 6th European Conference on Superplastic Forming Euro SPF 2008, Carcassonne (France).

[18] D. Sorgente, L. Tricarico. 2008. A numerical-experimental approach to material characterization and process analysis in the blow forming process. Proceedings of the 6th European Conference on Super plastic Forming Euro SPF 2008, Carcassonne (France).

[19] S.P. Sundar Singh Sivam, V.G Umasekar, Shubham Mishra, Avishek Mishra, ArpanMondal. 2016. Orbital cold forming technology - combining high quality forming with cost effectiveness - A review. Indian Journal of Science and Technology. 9(38), DOI: 10.17485/ijst/2016/v9i38/91426.

[20] S.P. Sundar Singh Sivam, M. Gopal, S. Venkatasamy, Siddhartha Singh. 2015. Application of Forming Limit Diagram and Yield Surface Diagram to Study Anisotropic Mechanical Properties of Annealed and Unannealed SPRC 440E Steels. Journal of Chemical and Pharmaceutical Sciences. pp. 15-22.

[21] S.P. Sundar Singh Sivam, VG Uma Sekar, K. Saravanan, S Rajendra Kumar, P Karthikeyan, K Sathiya Moorthy. 2016. Frequently used Anisotropic Yield Criteria for Sheet Metal Applications: A Review. Indian Journal of Science and Technology. Indian Journal of Science and Technology. 9(47), DOI: 10.17485/ijst/2015/v8i1/92107.

[22] Roy R.K. Desgin of experiments using the Taguchi approach, John Wiley and Sons. Canada.