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Sheet Metal Forming Analysis of Aluminium Alloy AA6061 using |Altair INSPIRE Form Simulation

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ABSTRACT

Altair INSPIRE Form is a computer simulation developed for designing and modelling sheet metal forming processes. Within the modules, the design and formability prediction can be simulated and optimized. Thus, this study focuses on analysing the formability of sheet metal Aluminium alloy AA6061 by simulating numerically a multistage forming of an end-wall process where the material properties and process parameters gained from the literature were used as input. The geometrical model was validated by comparing its formability with the literature that was simulated by Altair HyperForm. Then, to statistically analyse the influence of forming parameters on formability, Analysis of Variance (ANOVA) was applied with the design of experiment approach using the Response Surface Methodology (RSM). The simulation results observed similar strain rate distributions between Inspire Form and HyperForm under a safe forming process. For the formability of Aluminium alloy AA6061, loose metal zones with wrinkles, excessive thinning up to 23.13%, and the maximum equivalent stress at 414.6 MPa were expected to be generated. These findings clearly explained that forming parameters such as blank holder force and punch velocity have to be carefully controlled for this ductile material. The ANOVA shows a significant influence of coefficient friction and punch velocity on thinning percentages. The likelihood of tearing to form at a higher thinning percentage and its appearance was observed in the Forming Limit Diagram which evaluates its formability. The validation of optimized parameters by simulation work is concluded to be successful as no fracture appeared in this simulation with a small percentage error at 2.19% between the simulation and the predicted value.

Keywords: Altair Inspire Form; sheet metal forming; Response Surface Methodology (RSM); ANOVA

INTRODUCTION

Sheet metal forming (SMF) is a manufacturing process that is extensively used in the automotive, aerospace, and home appliance industries to produce high-volume, low-cost components such as car body panels, aircraft skins, electrical enclosures, and household appliances (Suliman 2006). The process transforms flat sheets of metal into complex shapes and structures through plastic deformation. This process relies on the ability of metals, especially ductile materials such as steel, aluminium, or copper, to undergo plastic deformation without breaking when subjected to compressive forces (Oliveira & Fernandes 2019). Usually, ductile materials are preferred because they can undergo significant plastic deformation without fracturing. The success of the SMF process relies on precise tool design, material selection, lubrication, and material behaviour during plastic deformation. Nevertheless, SMF processes are afflicted by several defects, such as cracking, localized necking, excessive thinning, and others, because of the multiple variables involved in forming processes.

The issue of defect prediction is further complicated by the seemingly random presence of forming defects due to scattering sources (Dib et al. 2018). According to Tekkaya (2000), the deformation kinematics in SMF, which also exhibits macro-scale instabilities causes necking and wrinkling. While spring-back and residual stresses are other critical issues that are usually observed during the process which are believed due to elastic unloading after elastoplastic deformation (Tekkaya 2000). As stressed by Kumar et al. (2016), and Matteo Candon (2023), the SMF process must be carefully planned and conducted to generate a stable and accurate analysis, particularly for each of the phenomena. Therefore, simulation tools, like finite element analysis (FEA), Inspire™ Studio, and HyperForm are often used to predict and optimize the forming process before actual production takes place.

Manufacturers have had to develop and employ new materials to further improve their product's performance. For instance, new materials were developed for structural components, body and trim to be aligned with the rise in consumer demand for green automobiles that are fuel efficient and greater safety (Suliman 2006). This introduces new obstacles for predicting the formability of sheet metals that cause most researchers to turn to the concept of Forming Limit Diagram (FLD) (Oliveira & Fernandes 2019). FLD is usually applied in the design stage to determine the formability and predict the failure points in a formed part as well as for optimizing variables of any new sheet metal (Hariharan & Balaji 2009). Thus, every new sheet metal that has its own properties, has also own its forming limit diagram which determines its formability, strain limit and forming regions (Kharkate & Gupta 2011). FLD represents the composition of two principal surface strains, which are major and minor strains that observe the fluctuation of localized necking. The curve drawn from pure shear to equibiaxial tension is called the Forming Limit Curve (FLC), and it shows how much a material can be stretched before it breaks. The region beneath this curve represents tolerable deformation, whereas the region above the curve often implies undesired deformation. Several experimental and mathematical models have been developed to develop the FLD and study the instability of sheet metal. The results of theoretical and experimental methods have been compared to prove the validity of both approaches (Kumar et al. 2016).

Establishing the FLD of a new material experimentally is known to be much more complicated and expensive, particularly at high temperatures. In metal forming, an FLD is used to predict the formability of sheet metal under various cutting conditions, from uniaxial tension to balanced biaxial stretching (Croteau et al. 2022). To identify the new materials' behaviour, many researchers turn to forming simulations that allow for analysing the material's behaviour during the forming process (Dib et al. 2018; Kharkate & Gupta 2011; Singh 2019). Altair Inspire Form is one of the new simulation software developed for the manufacturing industry to conduct a simulation of SMF processes. The software is also capable of analysing the probability of defects like fractures, wrinkles, earing, and others, which may occur during the SMF process. However, different materials may have different material properties which lead to variations in process performances. Furthermore, not all types of materials are available in Altair's library. Creating a new material in Altair requires necessary parameters and data which can be obtained through experimental work or modelling equations. According to Tiwari et al. (2016), a successful sheet metal forming operation relies on the suitable material selection and its properties. Another important input is the process parameters such as pressure, blank holder force, friction coefficient, and punch speed (Singh 2019).

Thus, this study focused on simulating the sheet metal forming process by Altair Inspire Form with the material properties of aluminium alloy AA6061. The material has a wide range of applications including as structural and automotive components (Mamgain et al. 2023). This approach allows for accurately predicting how the material will behave during the forming process and at the same time identifying potential quality issues along the process without costly physical prototypes and iterations. The parameters and the material properties of the material gained from the literature were inputted into Altair in order to create a material for running the formability analysis. Research on forming analysis of spoke resonator end-wall done by Tiwari et al. (2016) has been chosen as a case study in this study. A design of experiment approach was also conducted by Design Expert V10, using the Response Surface Method (RSM) of Box Behnken. Then, analysis of variance (ANOVA) was performed to analyse the influence of metal forming controlled factors which are binder force, friction coefficient and punch velocity on metal thinning.

METHODOLOGY

MODEL VALIDATION

In this study, the geometrical model of a spoke resonator end-wall was developed using CATIA V5 by referring to Sharma et al. (2020). Figure 1(a) illustrates the details dimensions of the CAD model. After that, the CAD model was imported into Altair Inspire Form where the forming tools such as die, punch and binder were created by selecting the specific surfaces of the imported model. The forming tools were arranged according to the real forming tool setup, where the punch and the blank holder were placed on top of the blank while the die was placed below the blank, as shown in Figure 1(b). The drawing direction of this forming process is downward. While the blank and die are in a stationary position, the blank holder moves downward until it contacts the blank, followed by the punch to form the blank into the shape of the die.

The accuracy of the numerical simulation results of sheet metal forming processes depends on the model selected for describing the material behaviour. To validate the accuracy of the simulation results by Altair Inspire Form, a study by Sharma et al. (2020) was replicated where they applied Altair HyperForm to analyse the forming process of Niobium. Though different simulation software was used, both software are complementary tools within the field of metal forming simulation. Table 1 shows the mechanical properties of the Niobium that were used as input into Inspire Form's Material Library for analysis. For the meshing, a medium-mesh size of 4 mm was applied. The simulation outputs generated by Altair Inspire Form and Altair HyperForm were compared in the forms of thinning percentage of sheet metal, equivalent stress on metal and formability in forming limit diagram.

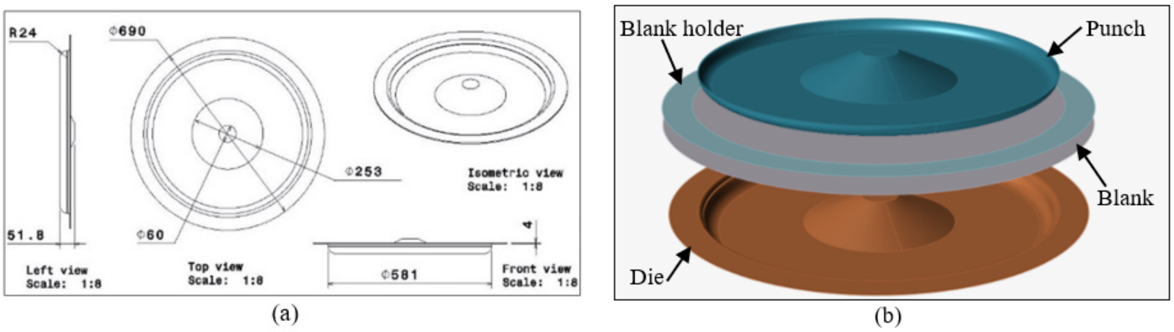


FIGURE 1. The forming model; (a) geometrical model (unit in mm), and (b) forming tools

To create material properties of aluminium alloy AA6061 in Altair Inspire Form, the chemical composition and mechanical properties from literature (Hao et al. 2017; Hussain et al. 2020) as shown in Tables 2 and Table 3, respectively were referred to simulate the forming process of a sheet metal of aluminium alloy AA6061 with a thickness of 2.0 mm. The material was created by filling in the data in the Material Library of Altair Inspire Form.

TABLE 1. Mechanical properties of Niobium (Croteau et al. 2022; Sharma et al. 2020)

Young's modulus (E)	Yield stress (σ_0)	Poisson's ratio (v)	Strength coefficient (K)	Strain hardening (n)	Lankford's coefficients		
					R_0	R_{45}	R_{90}
106 GPa	38 MPa	0.3	386.51 MPa	0.38	1.66	1.00	2.30

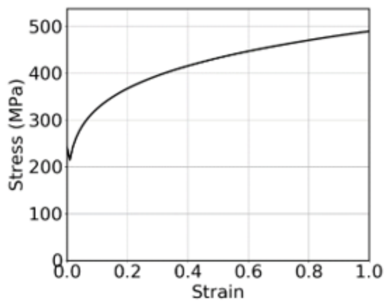
TABLE 2. Chemical composition of Aluminium alloy AA6061 (wt.%) (Hussain et al. 2020)

Material	Si	Fe	Mn	Mg	Cu	Ti	Cr	Al
AA6061	0.6	0.58	0.042	0.741	0.202	0.052	0.207	Bal.

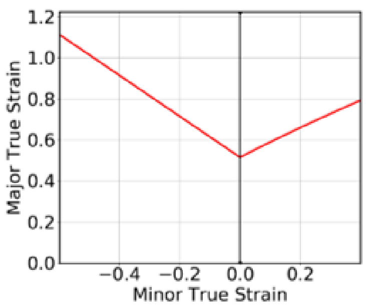
TABLE 3. Mechanical properties of Aluminium alloy AA6061 (Hao et al. 2017)

Young's modulus (E)	Yield stress (σ_0)	Poisson's ratio (v)	Strength coefficient (K)	Strain hardening (n)	Lankford's coefficients		
					R_0	R_{45}	R_{90}
74.6 GPa	244 MPa	0.314	489.74 MPa	0.179	0.55	0.52	0.53

In this study, Hill 1948 yield criterion was chosen for determining the anisotropy plastic behaviour of the newly created material while mixed cycle hardening was selected for the anisotropic hardening rule. These properties play significant roles in material behaviour as they involve the development of stress-strain curves and FLC of the material (Geng & Wagoner 2002). Figure 2(a) shows the stress-strain curve developed in the Altair Inspire Form after inputting the mechanical properties of aluminium alloy AA6061. This stress-strain curve is comparatively similar to experimental results conducted by Shi et al. (2013) on 6061-T6 aluminum alloy.



(a)



(b)

FIGURE 2. (a) Stress-strain curve of aluminium alloy AA6061 generated in Altair, and (b) Forming Limit Diagram of Keeler-Beizer (original) mode

The elastic behaviour in numerical simulation Altair was represented by the value of Young's modulus and Poisson's ratio. According to scientific studies, the Hill-Swift model is the common model used to analyse formability and is also being implemented in most numerical software (Hao et al. 2017).To account for the anisotropy condition, the behaviour of plastic material was numerically modelled using Hill's 1948 as in Equation 1 (Ailinei et al. 2022). *F, G, H, L, M,* and *N* are constants that are determined by the anisotropy property of the material.

$$(\sigma_{yy} - \sigma_{zz})^2 + G(\sigma_{zz} - \sigma_{xx})^2 + H(\sigma_{xx} - \sigma_{yy})^2 + 2L\sigma_{yz}^2 + 2M\sigma_{zx}^2 + 2N\sigma_{xy}^2 = 1 \quad (1)$$

Figure 2(b) shows the forming limit diagram of aluminium alloy AA6061 constructed in the Altair Inspire Form based on the inserted parameters. The software provides various models to form the FLD such as Keeler-Beizer model, NADDRG model and Abspoel-Scholting model. Altair Inspire Form also accepts data points input by which a set of major and minor strains are gained for experimental. The data can be directly pasted from the Excel file into the table provided to generate the forming limit curve. The forming limit is plotted based on the selected Keeler-Beizer (Original) model as shown in Figure 4.

ANALYSE FORMABILITY OF THE MATERIAL PROPERTIES BY ALTAIR

The properties of aluminium alloy AA6061 that have been saved in the Material Library were assigned to the blank sheet to validate its formability. The blank thickness was adjusted to 4 mm to match the case study (Sharma et al. 2020). The simulation was also performed with medium mesh sizing of 4 mm. The thinning percentage, equivalent stress, and formability pattern were analysed and compared with the referred case study in order to validate the accuracy of the newly created material as well as to observe its performance under the sheet metal forming process.

To analyse and understand how the process behaves under multiple controlled parameters as well as optimize the process by identifying the optimal combination of them, a statistical method of Analysis of Variance (ANOVA) was applied. In regression research, ANOVA determines the influence levels of independent factors on the dependent variable. In this study, the independent factors and their controlled levels are shown in Table 4, while the dependent variable or response that was analysed is thinning. Thinning refers to a phenomenon where the thickness of the metal sheet or workpiece decreases as a result of the forming operation as it undergoes plastic deformation to take on a new shape. It is a critical consideration in sheet metal forming to ensure that the final product meets thickness and quality requirements while avoiding defects such as blankness and facture (Billade & Dahake 2018; S. D. Kumar et al. 2016). Defects in thinning can be observed in FLD that are generated in the simulation result of the Altair Inspire Form. The minimum and maximum values of the controlled factors were determined by choosing the values that are lower and higher than the default value set by Altair, as well as through literature studies. By using Design Expert V10, 13 sets of parameters were designed under the Response Surface Methodology (RSM) of the Box-Behnken method. The optimization was also conducted with the main objective of minimizing the thinning percentage of the blank and fracture. The fracture occurrence can be observed from the formability result in FLD. The optimum response for this study was minimizing the thinning percentage. Thus, the optimum parameters for punch velocity and friction coefficient were set in range while the blank holder force was set to maximize in order to achieve the optimum response.

TABLE 4. Identified controlled factors and responses for optimization

No.	Controlled factors	Controlled ranges		Optimization	
		Minimum	Maximum	Response	Objective
1.	Binder force (kN)	100	300	Thinning percentage (%)	Minimize
2.	Friction coefficient	0.1	0.25		
3.	Punch velocity (mm/s)	3000	5000		

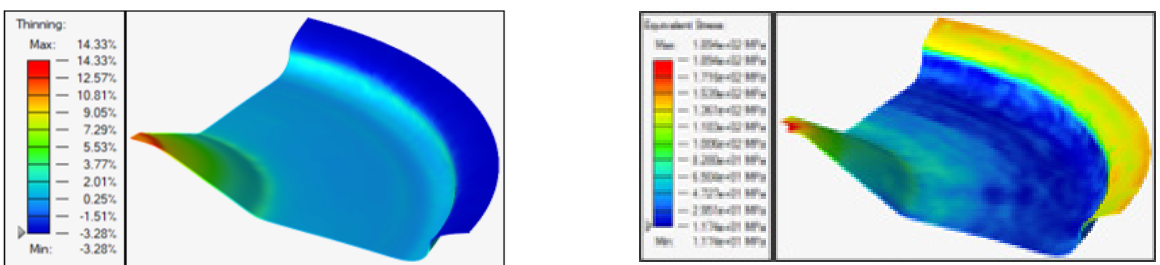
RESULTS AND DISCUSSION

MODEL VALIDATION

The forming analysis of the niobium spoke resonator end-wall in Altair Inspire Form resulted in the maximum thinning of 14.33% and maximum equivalent stress of 1.894×10^2 MPa, as displayed in Figures 3(a) and 3(b), respectively. When compared with Altair HyperForm by Sharma et al. (2020), they reported lower values with the maximum thinning percentage at 9.11%, as well as equivalent stress at 1.486×10^2 MPa. The differences between Inspire Form and HyperForm are 57.3% for thinning percentage, and 27.5%, for equivalent stress.

To analyse the forming defects such as wrinkling, necking, and failure during the sheet metal forming process, a forming limit diagram (FLD), which is the plot of plastic strain history, is employed. The maximum strain that a component can experience during various forming processes without failing is combined to generate the forming limit curve (FLC) (Geiger & Merklein 2003). To analyse the FLD, Sharma et al. (2020) and Kumar (2011) mentioned that the fracture limit is indicated by the red line where these areas are above the FLC of the material used. While for the marginal limit is by the yellow line, where thinning is higher than the acceptable value where there is a risk of crack, and the green line is the safe area with no formability problems on the formed components. Thus, it can be said that if the FLC lies between the marginal line and the green line, the component is deemed to be safe, however, if FLC lies beyond the red line, the component becomes fractured.

Figures 3(c) and 3(d) present the formability analysis of niobium by Inspire Form, and HyperForm (Sharma et al. 2020), respectively. For strain distribution, a similar distribution pattern of FLC from both software is observed. However, Inspire Form resulted in a smaller strain rate distribution than HyperForm, and they are located far from the fracture and marginal limit (red line).



(a) (b)

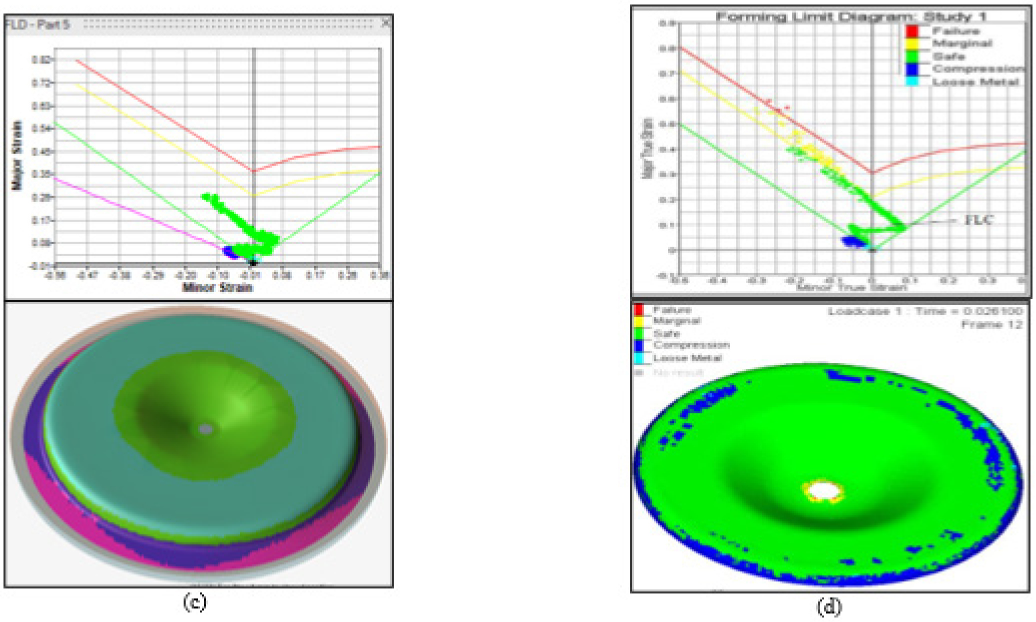


FIGURE 3. Simulation results from Altair Inspire Form; (a) thinning percentage, and (b) equivalent stress, (c) FLD and contour of formability analysis of Niobium by Inspire Form, and (d) FLD and contour of formability analysis of Niobium by HyperForm (Sharma et al. 2020)

Thus, it can be considered a successful and safe process as all strains are in the safe (green) region. Also, it can be observed from the model there is a purple region that indicates wrinkles are occurring on the flange area. There is a possibility of wrinkles forming on that area which cause defects like earing. According to Suliman (2006), areas that are unsupported or solely in contact with one tool may wrinkle. Increasing the blank holder force, which raises radial stress and strain, is the standard treatment.

According to Sharma et al. (2020), HyperForm resulted in a quite safe forming process as most of the strains are located below the fracture limit, as shown in Figure 3(d). However, some strains passed the marginal limits (yellow line), with a small number of them having passed the red limit curve which appeared at the centre nose area. Thus, failure is predicted to occur in that area. The blue region which is mostly on the radial side of the model means that the area experienced compression behaviour.

Thus, it can be said that the model used in this study is valid to be applied in the next analysis in order to develop material properties in Inspire Form. Even though the simulation results were slightly different, it can be accepted that the Inspire Form is designed for simulating and optimizing sheet metal forming processes, with a focus on the behaviour of the formed part. The HyperForm is specialized in simulating die design and processes, concentrating on the behaviour of dies and tooling (Engineering 2023).

FORMABILITY ANALYSIS OF ALUMINUM ALLOY AA6061

Figures 4(a) and 4(b) show the FLD and contour of formability analysis of aluminum alloy AA6061 by Inspire Form. The FLD shows that the strain distribution is lower than niobium (refer to Figure 4(a)). There is a large turquoise region on the base of the model indicating a loose metal zone. Loose metal is a condition where a region or area within a metal component undergoes excessive thinning or stretching during the forming process, resulting in a loss in material thickness. It may also happen when there is an area on the metal having no tension or compression acting on it resulting in maximum thickening (Kumar 2011). In contrast to the material around it, this zone frequently has a weaker and less stable structure. It may happen due to low punch/die stroke where careful control of punch/die clearances is required to produce a clean flange (Suliman 2006).

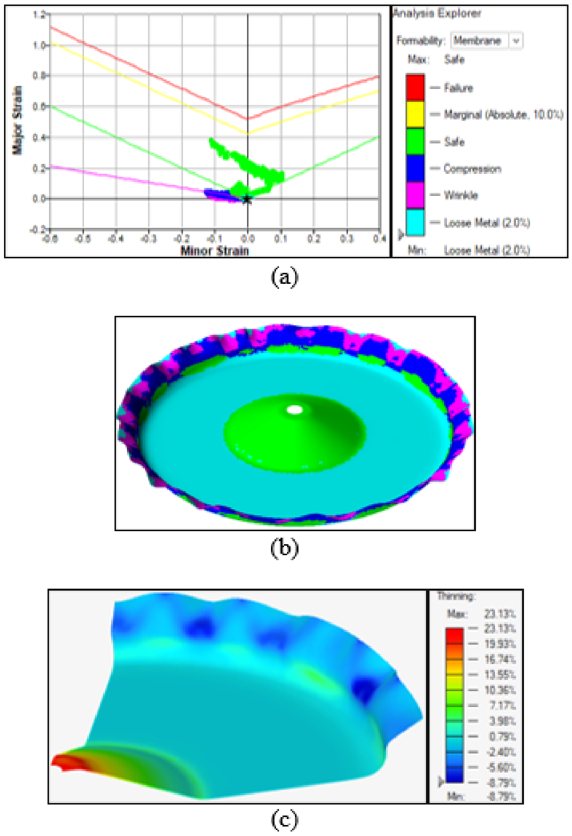


FIGURE 4. (a) FLD, (b) contour of formability analysis, and (c) Thinning percentage (%) of aluminum alloy AA6061

It also evidences high wrinkle concentration on the flange indicated by the purple colour caused the formation of earing. The wrinkle usually happens when the area experiences compressive strains which means the material becomes thicker during the forming process. The main cause is due to insufficient blank holder force applied to hold the end side of the circular blank during the forming process (Zein et al. 2014). Hence, increasing the blank holder force is one of the solutions.

By referring to Figure 4(c), it shows that the highest thinning happened at the centre nose region of the model. The whole conical area of the end-wall undergoes high thinning behaviour while the base and flange had least between 0.79% to 3.98%. As mentioned by Kumar (2011), higher forces are needed if the metal is folded over the conical area with a sharper radius, which causes excessive thinning or ripping around the area. Thus, the punch corner radius must be between 4 and 10 times the metal thickness in order to prevent excessive thinning. Punch corner radius is highly important since fractures frequently happen closer to it.

ANALYSIS OF VARIANCE (ANOVA) AND OPTIMIZATION OF THINNING PERCENTAGE

Table 5 shows 13 simulation layouts with the results of thinning percentage. This study found that the highest thinning percentage is 23.12% from run 2 with a binder force of 100 kN, friction coefficient of 0.1, and punch velocity of 4000 mm/s. The lowest is 21.21% from run 4 with a binder force of 200 kN, friction coefficient of 0.25, and punch velocity of 3000 mm/s. The simulation results are considered acceptable as no fracture was observed from the FLD of each simulation. It can be noticed also that the highest thinning percentage happened at the highest punch velocity, while the lowest happened at the lowest punch velocity.

TABLE 5. The Simulation Results

Run no.	Process parameters			Responses
	Binder force (kN)	Friction coefficient	Punch velocity (mm/s)	Thinning percentage (%)
1	100	0.25	4000	21.53
2	300	0.1	4000	23.12
3	100	0.175	3000	22.36
4	200	0.25	3000	21.21
5	100	0.1	4000	23.09
6	100	0.175	5000	22.92
7	300	0.25	4000	21.61
8	300	0.175	3000	22.4
9	200	0.25	5000	22.14
10	200	0.175	4000	22.75
11	200	0.1	5000	23.49
12	200	0.1	3000	22.46
13	300	0.175	5000	22.98

Table 6 displays the ANOVA after inputting the response values in Design Expert. From this analysis, the *F*-value of 132.76 implies that the model is significant. There is only a 0.01% chance that an *F*-value this large could occur due to noise. *P*-value is less than 0.05 indicating model terms are significant. Through model reduction, only factors *B*-friction coefficient, *C*-punch velocity, and B^2 are significant model terms. These factors provide significant influence on the thinning percentage with a dominancy of factor *B*.

TABLE 6. Analysis of Variance (ANOVA)

Source	Sum of squares	df	Mean square	*F*-value	*p*-value	
Model	5.60	3	1.87	132.76	< 0.0001	significant
B-Friction coefficient	4.02	1	4.02	285.90	< 0.0001	
C-Punch velocity	1.20	1	1.20	85.46	< 0.0001	
B^2	0.3785	1	0.3785	26.93	0.0006	
Residual	0.1265	9	0.0141			
Cor total	5.72	12				
Std. Dev.	0.1186		R^2		0.9779	
Mean	22.47		Adjusted R^2		0.9705	
C.V. %	0.5277		Predicted R^2		0.9496	
			Adeq. Precision		33.3387	

A second-order statistical equation model was developed by multiple regression and expressed in actual factors as shown in Equation 2. The model's 0.9779 determination coefficient (R^2) indicates that it accurately captures the real relationship between the variables and can be used to predict the value of thinning within the constrained parameters under study. Yet, the adequate precision of 33.33 which is larger than 4 shows an adequate signal that the model is fit and sufficient for prediction. Thus, Equation 2 can be used to make predictions about the response for given levels of each factor.

$$Thinning\ percentage = 22.682 + -0.70875 * B + 0.3875 * C + -0.35075 * B\hat{}2 \quad (2)$$

Figures 5(a) and 5(b) show the model graph of both significant factors. By referring to Figure 5(a), it can be seen that the increase in friction coefficient reduces the percentage of thinning. This might happen due to the reduction of distribution in blank thickness with the increase of the coefficient of friction between punch and blank. While Suliman (2006) recommended 0.15 for sheet steel and 0.18 for aluminium friction coefficient between sheet and tools. The punch velocity as in Figure 5(b) provides a contradictory impact as the thinning increases with the increase of its values. This is aligned with Kumar (2011), who mentioned that high punch velocity causes too much thinning, particularly for lesser ductile metals. Thus, adequate lubrication is recommended to generate an ideal condition for the forming process. It also helps to reduce the coefficient of friction, making it easier for materials to slide through tools (Suliman 2006).

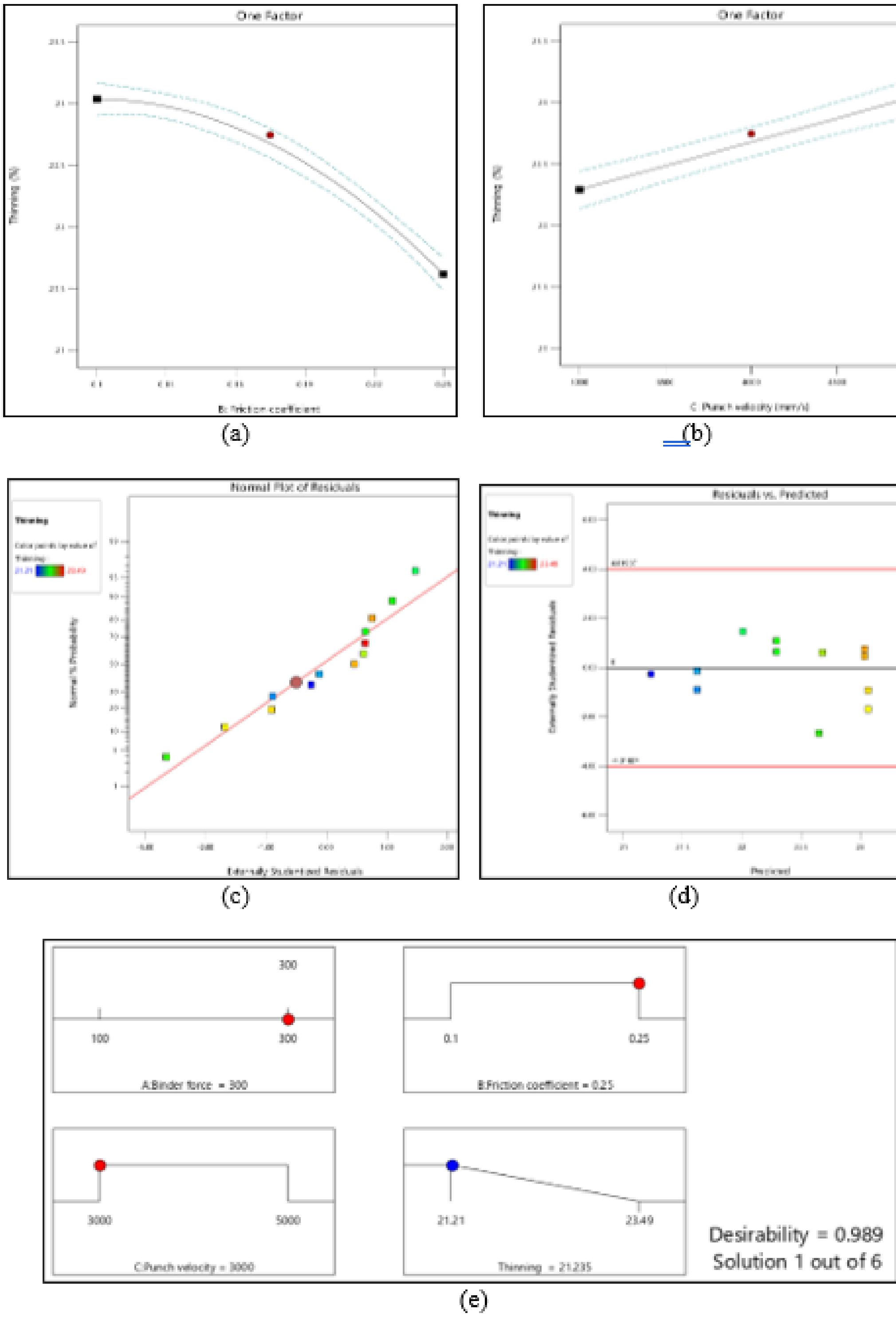


FIGURE 5. Outputs from ANOVA, diagnostic model, and optimization; (a) model graph for friction coefficient, (b) model graph for punch velocity, (c) normal plot of residual, (d) residual vs. predicted, and (e) Ramps model for optimization

The diagnostic plot of the normal plot of residuals and the residual vs. predicted plot, as illustrated in Figures 5(c) and 5(d), respectively were evaluated to ensure that the data was fit and acceptable. According to the normal plot of residuals in Figure 5(c), all of the residual data were near the line, indicating that the data are consistent with the normal distribution. Figure 5(d) of the residual vs. expected plot reveals that there is no apparent pattern or distinctive structural model because all the data are within the red boundaries.

A total of 20 solutions were generated to get the optimum value of parameters to produce the lowest thinning percentage. The binder force was set to the maximum value to firmly hold the circular blank when it was being punched, while the friction coefficient and punch velocity were set in range. Figure 5(e) shows the ramps model for optimum parameters and response under solution number 1 which has the highest desirability at 0.989. The lowest thinning at 21.235% is predicted at a binder force of 300 kN, friction coefficient of 0.25, and punch velocity of 3000 mm/s.

The optimum parameter was validated through simulation work. A thinning at 21.359% was recorded with an error of 2.19% when compared with the predicted value. This small error indicates that the simulation is valid and successful. By referring to Hayati et al. (2019), the generated prediction model is acceptable when its average error is less than 10%. This is also aligned with the practice of Tharazi et al. (2020) when they validated an optimum parameter for the hot pressing process.

CONCLUSION

In conclusion, this study has provided valuable insights into the formability of Aluminium alloy AA6061 sheet metal using Altair Inspire Form as a primary simulation tool. The study initiated the replication of a simulation from the literature, focusing on the spoke resonator end-wall made of niobium, which served as a crucial step in validating the model used in subsequent analyses. Then, the formability analysis of Aluminium alloy AA6061 sheet metal through simulation within Altair Inspire Form, utilizing material properties and process parameters acquired from comprehensive literature sources. Thus, it can be said that the geometrical model used in this study is valid to be applied in the next analysis to develop material properties in Inspire Form. Despite minor variations in simulation results, they remain well within acceptable bounds, confirming Inspire Form's strength in simulating and understanding the behaviour of the formed components. This study further investigated the significant relationship between controlled forming parameters and thinning percentages, employing the Response Surface Methodology (RSM) through Box Behnken Design and ANOVA. Results show that the lowest thinning percentage is predicted to be produced at a binder force of 300 kN, friction coefficient of 0.25 and punch velocity of 3000 mm/s. Remarkably, the error of 2.19% was recorded when comparing the actual thinning percentage of 21.359% to the predicted value of 21.235% affirming the reliability and success of the simulation approach employed. This study not only advances our understanding of the formability of Aluminium alloy AA6061 sheet metal but also emphasizes the reliability of the modelling approach employed. These findings lay a strong foundation for further research and development in Inspire Form, with the potential to unlock new possibilities in the field of material properties and sheet metal forming processes.

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DECLARATION OF COMPETING INTEREST

None

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