Prediction of the impact of friction’s coefficient in cylindrical deep drawing for AA2090 Al-Li alloy using FEM and Taguchi approach

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Abstract. To produce different cups from sheet metal, deep drawing is a vital process demanded by different industries such as automobile, aeronautics and so on. The comprehension of the process’s mechanics led to the correct determination of the factors which affect the deep drawing results. Experimental tests and numerical simulations are two significant ways for analysing the deep drawing process. Experimental tests are beneficial in studying the process to control the defect of the final product. However, to gain time and substantially reduce costs the numerical modelling became a common method which could be investigate the deep drawing technique through all steps of deformation. The Coulomb friction in contact regions is one of the most influencing parameters during deep drawing. This research emphasizes the influence of friction coefficient on deep drawing in three different regions: between blank surface and punch, blank surface and die, and blank surface and blank holder. For this purpose, a 3D Finite Element Model of AA2090 Al-Li alloy was carried out to simulate the process using ABAQUS software with A combination of the statistical approach based on Taguchi Techniques in order to predict the impact of friction coefficient Thickness variation have been studied, and the thinning region have been analysing for a cylindrical deep drawing process the results obtained were used as imputes of Taguchi method and the most appropriate combination of the Coulomb friction in the three regions concerning AA2090 Al-Li alloy was found.

1. Introduction
Aluminium is one of the lightest sheet metals which are very demanded in the aeronautic industry to satisfy the demands of environmental protection and fuel economy. In recent years, the Al-Li alloys have attracted increasing interest worldwide for large-scale applications in the aerospace industry, mainly due to soaring fuel prices and the development of a new generation of civil and military aircraft. Lithium is the lightest metallic element, it’s the only metal when it’s alloyed to aluminium the density decreases and the elastic modulus improves, the addition of 1% of Li could reduce 3% in density, and nearly raises 6% in elastic modulus [1,2]. Moreover, adding 2% lithium, the density is decreased by 10%, and the modulus of elasticity is increased by 25% to 35% [3], furthermore, the aluminium-lithium alloy has high specific strength, specific stiffness, high modulus of elasticity, instead of the conventional
high-strength aluminium alloy, the structural quality can be reduced by 10% to 20%, and the rigidity is increased by 15% to 20% [4].

Three generations of Al-Li alloys were obtained [5]. The third-generation alloys began in the late 1980s and is ongoing, and is considered to be the main structural material of the 21st century aircraft [6-8].

An important part of manufacturing is covered by sheet metal forming industry from kitchen to aircraft. Deep drawing process is one of the most widespread sheet metals forming techniques, it contains a great pact of plastic bending, sliding and unbending phenomena of the held blank between die and blank holder [9]. The deep drawing process is categorized by high efficiency and excellent surface quality of the deep drawn part.

Several factors affect the quality of the metal sheet forming during the deep drawing process such as yield criteria, the geometry of the design, the process parameters and the improper definition of these parameters led to failures like earring [10], wrinkling [11] and thinning [12]. A strong affectation of strain during formability appears due to the big contact surface with the tool compared to the sheet cross sectional region [13]. Therefore, the deep drawing manufacture of sheet metal is extremely affected by the friction condition. [14] analysed a combination between finite element method and experience to evaluate the coefficient of friction between the blank and tools. [15] studied a friction model by the friction condition, that was a generalization of non-associated sliding rule was defined using isotropic Coulomb’s frictional contact law to anisotropic friction conditions. [16] used Finite element method to investigate a high frequency vibration to decrease friction. [17] analysed a theoretical approach on friction limit surfaces and sliding rules. [18] investigated the impacts of friction coefficient alteration on the required punch load for forming and thickness reduction. [19] investigated the effects of forming parameters, including lubrication type and lubrication position, on the drawing formability. [20] carried out FEM simulation and investigated the contact situation between the die and the lubricant coated steel sheet through varying the friction coefficient between the die and the lubricant layer.

The friction phenomenon and its impact on thinning in deep drawing has been studied under different coefficient of friction between blank and die, blank and holder and blank and punch. For this purpose, finite element model has been carried out using a 3D modelled by ABAQUS software with a combination of Taguchi orthogonal test design method in order to optimize the coefficient of friction in the three different regions.

2. Numerical modelling of deep drawing

In the present paper the modelling of the deep drawing process was carried out by ABAQUS which was used as finite element software. The 3D quarter model of cylindrical deep drawing was modelled with the corresponding symmetry boundary conditions as it is shown on figure 1, the mass scaling as well was used in order to reduce the CPU time and save computer memory.

![Figure 1. Finite element model of deep drawing process: (a) After deformation; b) During deformation.](image-url)
The problem studied on this paper is the effect of friction condition on the thinning of deep drawing of AA2090 Al-Li material. The mechanical properties of AA2090 Al-Li alloy are shown on the table 1. The material is used with a thickness of 1.5 mm, the blank holder force is 22.2 kN, the blank diameter is 158.76 mm, the die diameter is 101.48 mm, the punch diameter is 97.46 mm, die and punch shoulder radius are 12.70 mm both [21].

Table 1. Mechanical properties of AA2090 Al-Li Alloy.

| Density (Kg/dm³) | Young’s modulus $E$ (GPa) | Poisson’s ratio $\nu$ | Hardening law $\sigma = 646(0.025 + \varepsilon)^{0.227}$ |
|-----------------|---------------------------|----------------------|--------------------------------------------------|
| 2.89            | 78.6                      | 0.3                  |                                                  |

The die, punch and holder were modelled as rigid bodies whose motion was governed by the reference node and were meshed with (R3D4) surface elements, while the blank was modelled as a deformable body, using reduced integration shell element (S4R) [22].

3. Taguchi design

A combination between FEA simulation and the statistical Taguchi approach was analysed to study the effects of contact between the sheet blank and the three rigid tools. The orthogonal Taguchi array adjacent the design such a method that parameter levels are similarly weighted. Due to this, each factor can be evaluated separately of all the other factors, therefore, the impact of one factor does not influence the estimation of another factor.

Under three levels of each factor as illustrated in table 2. The values of chosen control parameters were based on the results of [23] the models were conducted so as to predict the thinning on cylindrical deep drawn process using relevant ranges of friction coefficient, L9 orthogonal array had used to conduct the only nine simulations. The assignment of parameters along with the OA matrix is shown in table 3. Taguchi approach is most powerful Design of experiments (DOE) tool for parametric optimization of engineering process in the tool the concept of Signal to Noise ratio (S/N ratio) is used for improvement of quality through variability reduction and improvement of measurement [24].

Table 2. Process parameters and their levels.

| Process parameter                              | Levels |
|-----------------------------------------------|--------|
| Coefficient of friction between blank and die $\mu_d$ | 0.14   |
|                                              | 0.16   |
|                                              | 0.18   |
| Coefficient of friction between blank and holder $\mu_h$ | 0.14   |
|                                              | 0.16   |
|                                              | 0.18   |
| Coefficient of friction between blank and punch $\mu_p$ | 0.1    |
|                                              | 0.15   |
|                                              | 0.20   |

Table 3. Orthogonal array (L9) of Taguchi method.

| Treatment No | Coefficient of friction between blank and die $\mu_d$ | Coefficient of friction between blank and holder $\mu_h$ | Coefficient of friction between blank and punch $\mu_p$ |
|--------------|------------------------------------------------------|------------------------------------------------------|-------------------------------------------------------|
| 1            | 0.14                                                  | 0.14                                                  | 0.1                                                   |
| 2            | 0.14                                                  | 0.16                                                  | 0.15                                                  |
| 3            | 0.14                                                  | 0.18                                                  | 0.2                                                   |
| 4            | 0.16                                                  | 0.14                                                  | 0.15                                                  |
| 5            | 0.16                                                  | 0.16                                                  | 0.2                                                   |
| 6            | 0.16                                                  | 0.18                                                  | 0.1                                                   |
| 7            | 0.18                                                  | 0.14                                                  | 0.2                                                   |
| 8            | 0.18                                                  | 0.16                                                  | 0.1                                                   |
| 9            | 0.18                                                  | 0.18                                                  | 0.15                                                  |
4. Results and discussion

According to the test factor and the number of levels, Orthogonal test L9 (3^3) is used to develop orthogonal array (OA). S/N ratio had determined for every Finite Element Analysis simulation and the values of thinning obtained from each model is listed in table 4.

| Treat No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----------|---|---|---|---|---|---|---|---|---|
| Thinning (mm) | 1.335 | 1.422 | 1.421 | 1.418 | 1.442 | 1.325 | 1.4394 | 1.319 | 1.308 |

After the nine tests, Taguchi analysis was done and in order to investigate the optimal level of the coefficient of friction on the deep drawing process as shown in table 5. The optimum levels of the three factors given above. In order to obtain ameliorate the thinning in the final drawn cup and the percentage of the contribution of each factor on the quality of the drawn shape as shown in table 6.

| Level | µd | µh | µp |
|-------|----|----|----|
| 1     | 2.877 | 2.904 | 2.455 |
| 2     | 2.887 | 2.883 | 2.812 |
| 3     | 2.636 | 2.613 | 3.133 |
| Delta | 0.251 | 0.291 | 0.678 |
| Rang  | 3    | 2   | 1   |

| Process parameters | Level | Contribution % |
|--------------------|-------|----------------|
| µd                 | 2     | 27             |
| µh                 | 1     | 33             |
| µp                 | 3     | 40             |

| Thinning (mm) | 1.4445 |

From figure 2 it is detected that the optimum condition to reduce thinning is µd at Level2, µh at Level1 and µp at Level3. An extra run was done again by FEA simulation to confirm the results obtained by Taguchi analysis and it was found that the combination of the levels that the value of thinning is 1.4445 mm which is the bigger values compared to the results of tests in table 4 which confirmed the validation of Taguchi method.
5. Conclusion
Friction is one of the pertinent parameters which affect the quality of final drawn shape. Therefore, a numerical simulation for the prediction of friction effect of AA2090 Al-Li alloy sheet were achieved using ABAQUS/EXPLICIT software. In this study a combination between finite element analysis and the statistic Taguchi method was used. As a result, the best combination of friction coefficients to enhance the quality of the final drawn shape of AA2090 is 0.16, 0.14 and 0.20 concerning $\mu_d$, $\mu_h$ and $\mu_p$ respectively, as well the friction between punch and blank is the most contributed parameter with a percentage of 44% followed by the coefficient of friction between the blank and holder with a percentage of 33% and the less contributed is the coefficient of friction between die and blank with a percentage of 27%.

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