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Analysis of 6061 Aluminium Alloy Sheet Metal Bending Process for Various Thickness Using Finite Element Modelling

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Abstract: This study elaborates the bending process of Al 6061 aluminium alloy using three-point bend test. The permanent deformation takes place on the sheet metal strip as a result of severe plastic strain. One of the major issues in the sheet metal bending process is that the formation of spring back during unloading. This study involves combined design of experiment and finite element analysis to understand the bending and spring back behaviour of sheet metal. The elasto-plastic behaviour is studied by parametric numerical simulations. The static mechanical behaviour at ambient temperature is investigated for various thickness and radius of punch to achieve its correlations. The systematic approach is carried by developing numerical models of three-point bending of aluminium strips.

Keywords: FEA, DOE, Bending, Manufacturing, Aluminium

1. Introduction

The sheet metal bending process produces permanent deformation in component to be bent. It can be achieved by applying a force that can produce localized plastic strain in the component. Due to localized plastic deformation, the component is induced with residual stress. Since the deformation consists of elastic and plastic deformation, the component tries to recover its initial shape that is called as spring back. There are many reference articles published by researchers on the bending analysis. The authors [1] investigated cold-formed normal and high strength stainless steel square and rectangular hollow sections subject to major axis bending. A non-linear finite element model which includes geometric and material non-linearities was developed and verified against experimental results.

The authors [2] investigated the results of a comprehensive experimental-numerical study aimed at determining the flexural performance of cold-formed laterally-restrained steel rectangular hollow flange beams. Results of the experimental study that consisted of material characterisation and tests on full-scale specimens are thoroughly presented. The objective of this work [3] was to provide a simplified method for predicting the bending stiffness of thin-walled cold-formed steel members subject to elastic (or inelastic) local buckling. Although existing design specifications provide some guidance on how to predict the stiffness, limited information is available for cross-sections subject to distortional buckling or undergoing inelastic local and/or distortional buckling.

The authors [4] presented, a novel approach to measure the Bauschinger effect, transient behaviour and permanent softening of metallic sheet subjected to reverse loading. The hardening parameters related to the Bauschinger effect, transient behaviour and permanent softening are optimized from the springback profiles of three-point bending tests with pre-strained sheets. A new technology to eliminate springback of HSS sheets in U-bending process was reported [5], where the bottom plate is additionally bent with a counter punch at the final stage of U-bending process. The U-bending process

consists of four steps starting with clamping of a sheet between a punch and a counter punch, then U-bending with constant clamping force followed by bottom pushing-up by the counter punch, and final unloading process.

Hollow structural sections (HSS) are desirable for utilization in structural applications due to their inherent flexural, compression, and torsional properties [6]. To address the limited experimental data and determine potential limiting parameters for the use of HSS in seismic bending applications, a finite element model (FEM) considering experimentally measured material properties, section geometry, and geometric imperfections has been calibrated and validated to experimental findings.

A review on springback elucidates one of the most sensitive features of the sheet metal forming that is the elastic recovery during unloading [7, 8]. Sheet metals are prone to some amount of spring back depending on elastic deformation. Obtaining the desired size, shape depends on the prediction of spring back. Accurate prediction and controlling of spring back is essential in the design of tools for sheet metal forming. The spring back is affected by the factors such as sheet thickness, material properties, tooling geometry etc. This paper reviews the various parameters affecting spring back such as ratio of die radius to sheet thickness, sheet thickness, blank holder force, coefficient of friction etc.

The accuracy for cold-bending springback prediction is determined by the sensitivity and accuracy of the material constitutive model [9]. Thus, the material constitutive model is developed and improved by many researchers, and the improved models are applied in the springback calculation with various materials in finite element simulation or theoretical analysis. To provide a reference for the researchers studying cold bending springback problems, a review of the development and application of the material constitutive models was presented.

The authors [10] deals with the overcoming springback on U bending. Many research and study have been done on a springback. In sheet metal bending, a flat part is bent using a set of punches and dies. The punch and the dies are mounted on a press machine, which control the relative motion between the punch and die and provides the necessary bending pressure. The authors presented [11] to achieve a high precision of parts, especially the required bending angle, a suitable design of process parameters is strictly considered. In this study, process parameters of bending angle, material thickness and punch radius were investigated. The finite element method (FEM), in association with the Taguchi and the analysis of variance (ANOVA) techniques, was carried out to investigate the degree of importance of process parameters in V-bending process.

The research on curved structural wide flange steel sections are presented [12]. These sections are usually curved at ambient temperatures with a roller bending machine. This process alters the residual stress distribution, which may affect the elasto-plastic buckling behaviour of arches. This paper presents a numerical modelling technique to estimate residual stresses in curved wide flange sections manufactured by the pyramid roller bending process. It is noticed from the literature that there is limited research taken place that systematically correlate the experimental parameters. In this research, the design of experiment was employed to correlate the input and response that was obtained from the numerical simulations.

2. Three Point Bending Strategy

The problem set up and the required parameters to be studied is shown in Figure. It has two roller supports which are firmly fixed such that it won't move during loading. The distance between two rollers is set as constant. An aluminium strip is placed on two roller supports which is fixed at a distance of D. The strip is loaded with cylindrical punch at its centre of span to make it bend. The punch pushes the aluminium strip with various downward distance of L and the resulting structural effects are monitored. In this experiment, the distance between two roller supports (D), displacement load (L) and sample thickness (t) are considered as variable.
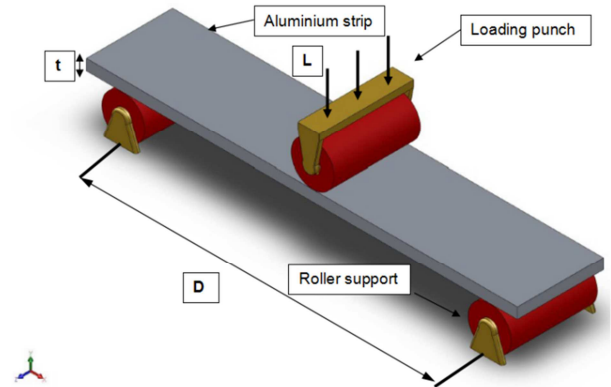

Figure 1. *Problem Setup.*

3. Box-Behnken Design

Box-Behnken designs are response surface designs, specially made to require only 3 levels, coded as-1, 0, and +1. They are formed by combining two-level factorial designs with incomplete block designs. This procedure creates designs with desirable statistical properties, but, most importantly, with only a fraction of the experiments required for a three-level factorial. Numerical analyses were performed based on a Box Behnken design with three factors at three levels and each independent variable were coded at three levels between −1, 0 and +1. The total number of experiments (N) was calculated using Eqn (1):

$$N = K^2 + K + C \qquad (1)$$

Where, K is the factor number and C is the replicate number of the central point. A linear regression method was used to fit the first order polynomial Eqn. (2) to the experimental data and to identify the relevant model terms. The linear response model can be described as,

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + e_i \qquad (2)$$

Where, Y is the response; x_i is variable (i range from 1 to k); β_0 is the model intercept coefficient; β_i is interaction coefficients of linear terms; k is the number of independent parameters (k=3); and e_i is the error. Table shows the range of input parameters used in the analysis.

Table 1. Input parameters.

Parameter	Sample thickness (m)	Displacement load (m)	Distance between rollers (m)
min	0.004	0.01	0.1
max	0.01	0.02	0.15

The following Table 2 shows the design matrix of input parameters to be analysed.

Table 2. Design matrix.

S. No	Factor 1	Factor 2	Factor 3
	Sample thickness	Displacement load	Distance between rollers
	m	m	m
1	0.007	0.01	0.1
2	0.01	0.015	0.1
3	0.004	0.02	0.125
4	0.01	0.015	0.15
5	0.007	0.015	0.125
6	0.004	0.015	0.15
7	0.007	0.01	0.15
8	0.007	0.02	0.15
9	0.01	0.02	0.125
10	0.004	0.01	0.125
11	0.007	0.015	0.125
12	0.007	0.02	0.1
13	0.01	0.01	0.125
14	0.004	0.015	0.1

4. Finite Element Analysis of Bending

The numerical simulation was carried out using Abaqus software and the detailed procedure is discussed. The analysis involved aluminium strip that was supported by two rollers and load was applied using a cylindrical punch. The CAD models were generated using Abaqus part module and partitioned to have reference points. Based on the design matrix models were generated and analysed separately. The models were generated as 2D and plane stress condition was considered.

Three point bending induces plastic strain at the center of the component by which the component is bent. To facilitate the permanent deformation, the model was assigned with material's flow curve details. As the analysis focused on the bending strip, it was assigned with elastic-plastic material property whereas the rollers were not investigated and thus it was assigned with elastic property only. The analysis setup was made in assembly module. Required number of roller and bending strip of CAD models were brought into the assembly module and moved to appropriate positions. Figure shows the
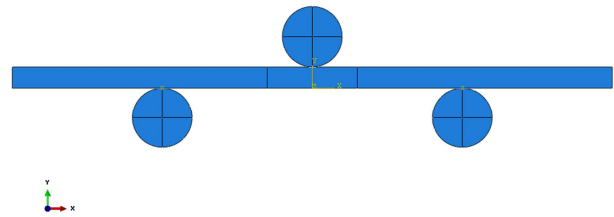
models that were assembled appropriately.

Figure 2. Model assembly.

The surface to surface contact conditions between rollers and strip was assigned between components. The rollers and punch was established similar contact conditions. Contact surfaces were assigned with tangential and normal contact. Penalty approach was employed with coefficient of friction as 0.3. Also the surface of punch was coupled with center control point for loading. The control point and surface point were considered with UX, UY and UR in the 2D coordinate.

4.1. Loading and Boundary Conditions

Based on the physical understanding the roller support is rigid and the strip was placed on the support. Later the punching was applied to bend the strip. By understanding this, the roller support was fully fixed. The punch was assigned with displacement boundary, i.e. the punch was pushed to predefined distance from its initial position.

The analysis was carried out in two load steps. First step was loading and second step was unloading. During first load step the punch was moved downward and second load step its position was assigned as 0, i.e. it would come back to original position. Since it involved plasticity, it was solved by having non-linear geometry and higher iteration increments.

4.2. Meshing

The model was meshed with structured elements. In order to get fine results, the centre zone of strip was meshed with smaller element and away from the centre was assigned coarse elements. Rollers were swept meshed to have structured mesh alignments. The model was assigned with plane stress element named as "CPS4R: A 4-node bilinear plane stress quadrilateral, reduced integration, hourglass control".
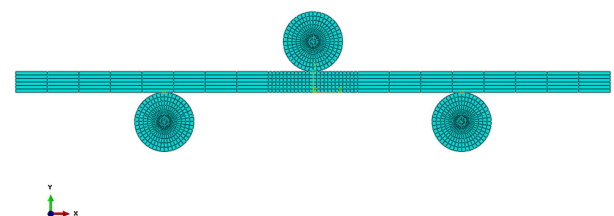

Figure 3. Meshed components.

4.3. Analysis and Post Processing

After assigning boundary conditions, loading and meshing, a job file was created to solved the problem and submitted to the solver. It took many iterations to complete the problem and

the results were extracted. The following figures show the results of loading and unloading step of each trials as per design matrix. It is clearly noticed that the components were induced higher stress during loading and still it was induced with stress after unloading step. The stress that was presented after unloading step is called as residual stress. It is due to the presence of induced plastic strain in the bending strip.

5. Result and Discussion

5.1. Correlation Between Input Parameter and Springback

The correlation was generated based on the analysis of variance (ANOVA). The ANOVA table for spring back is shown as follows,

Table 3. *ANOVA for Spring back.*

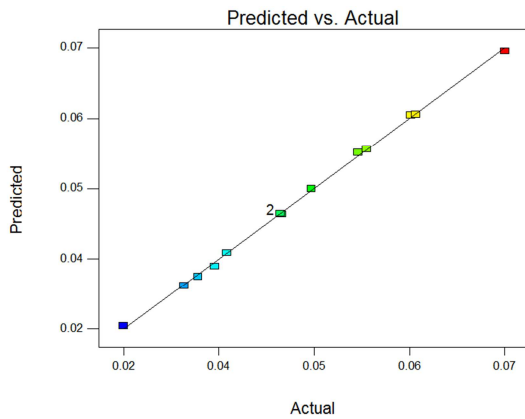| Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	0.002452	9	0.000272	509.9413	< 0.0001	significant
A-Sample thickness	0.001405	1	0.001405	2630.766	< 0.0001	
B-Displacement load	8.43E-06	1	8.43E-06	15.77992	0.0165	
C-Distance between rollers	0.000976	1	0.000976	1827.71	< 0.0001	
AB	4.73E-06	1	4.73E-06	8.864163	0.0408	
AC	5.25E-06	1	5.25E-06	9.824208	0.0350	
BC	2E-06	1	2E-06	3.752742	0.1248	
A^2	4.47E-05	1	4.47E-05	83.68821	0.0008	
B^2	8.28E-07	1	8.28E-07	1.549634	0.2811	
C^2	6.73E-07	1	6.73E-07	1.259646	0.3245	

Figure 4. *Prediction of springback.*

The correlation was checked for main and interaction effects using a quadratic model. Based on the ANOVA table the probability of significant parameters were checked. The model was considered as significant if the probability falls less than 5%. Based on this consideration all the main effect and interaction effects were analysed. The following figure shows the actual and predicted data of springback. The linear curve fit shows very close agreement of actual data that falls with linear relation. The variation of actual data from the prediction is very less which gave close predictions.

The mathematical relationship of springback and input parameters is represented by the following equation, $(\text{Spring back})^{1/2}=[+0.026816 - 7.23494 * \text{Sample thickness} - 1.01580 * \text{Displacement load} + 0.64726 * \text{Distance between rollers} - 72.53288 * \text{Sample thickness} * \text{Displacement load} - 15.27196 * \text{Sample thickness} * \text{Distance between rollers} + 5.66333 * \text{Displacement load} * \text{Distance between rollers} + 415.29042 * \text{Sample thickness}^2 + 20.34403 * \text{Displacement load}^2 - 0.73368 * \text{Distance between rollers}^2]$

Based on the above mentioned equation, the surface plots of correlation are generated. The following surface plot shows the influence of sample thickness and displacement load on springback. It is noticed that the displacement load varies between 0.01m to 0.02m which has negligible influence on the spring back. It did not affect the springback throughout its range. But sample thickness has significant influence on spring back. The springback is reduced when the sample thickness is increased.
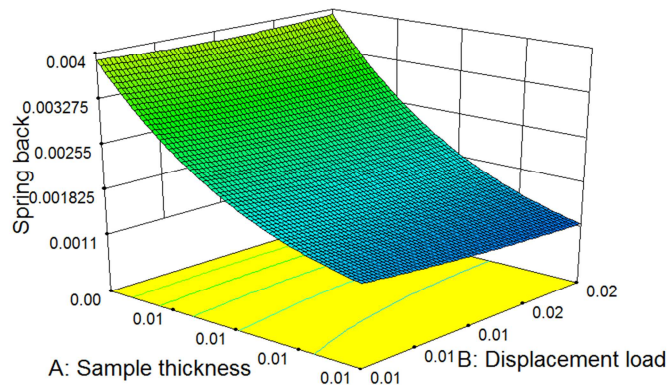

Figure 5. *Spring back on A and B.*

The following surface plot shows the influence of sample thickness and distance between roller support on springback. The springback is reduced when thickness is increased and the springback is increased when the distance between rollers is increased. Also noticed that the interaction of lower thickness and maximum distance between roller support yields higher springback.
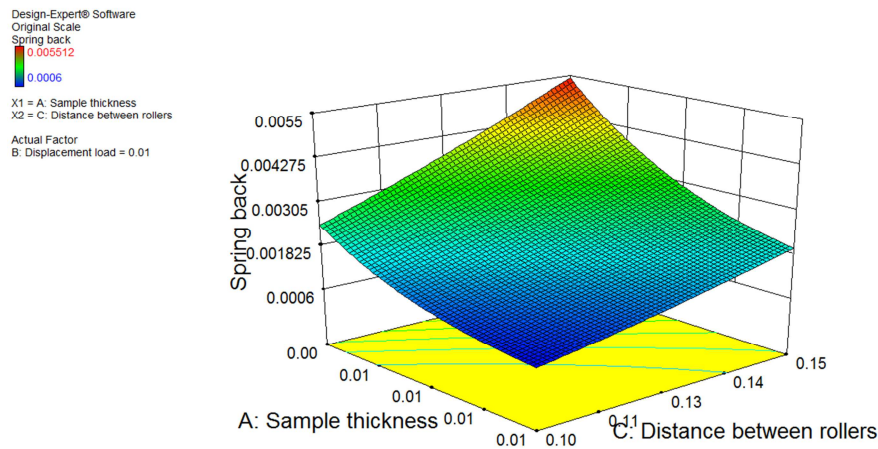

Figure 6. Spring back on A and C.

The following surface plot shows the influence of distance between roller and displacement load on the springback. It is clear that the displacement load has negligible influence whereas the distance between rollers has significant influence on the spring back. When the distance between rollers increased the springback also increased.
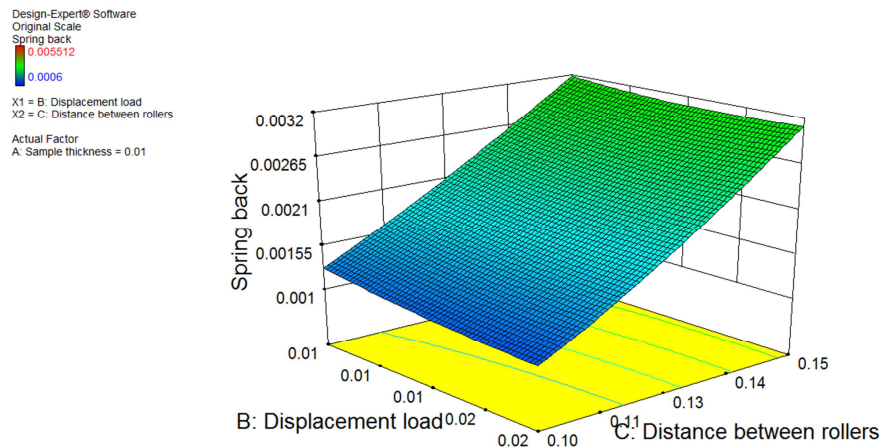

Figure 7. Spring back on C and B.

Based on the above mentioned surface plot overall, it is noticed that the displacement load during analysis has no effect on the spring back whereas the sample thickness and distance between rollers has significant influence on the springback.

5.2. Correlation Between Input Parameter and Residual Stress

The correlation was generated based on the analysis of variance (ANOVA). The ANOVA table for residual stress is shown as follows,

Table 4. ANOVA for residual stress.

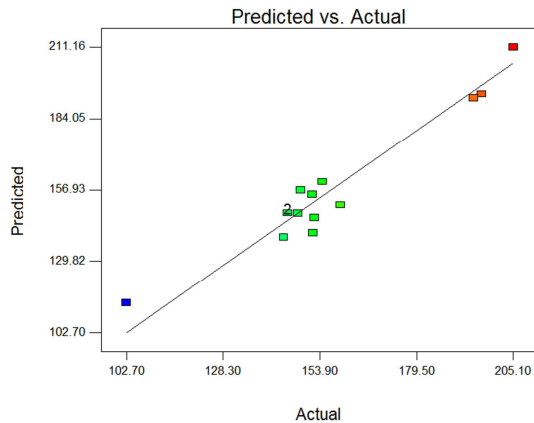| Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	8302.045	9	922.4494	6.637132	0.0420	significant
A-Sample thickness	1749.361	1	1749.361	12.58686	0.0238	
B-Displacement load	2471.045	1	2471.045	17.77946	0.0135	
C-Distance between rollers	148.7813	1	148.7813	1.070499	0.3593	
AB	612.5625	1	612.5625	4.40746	0.1037	
AC	615.04	1	615.04	4.425285	0.1032	
BC	1819.023	1	1819.023	13.08808	0.0224	
A^2	798.848	1	798.848	5.747806	0.0746	
B^2	22.05	1	22.05	0.158652	0.7107	
C^2	12.168	1	12.168	0.08755	0.7820	

Figure 8. Residual stress prediction.

The correlation was checked for main and interaction effects using a quadratic model. Based on the ANOVA table the probability of significant parameters were checked. The model was considered as significant if the probability falls less than 5%. Based on this consideration all the main effect and interaction effects were analysed. The following figure shows the actual and predicted data of springback. The linear curve fit shows very close agreement of actual data that falls with linear relation. The variation of actual data from the prediction is very less which gave close predictions.

The mathematical relationship of residual stress and input parameters is represented by the following equation, Residual stress=-234.68611-11356.94444 * Sample thickness +15915.00000 * Displacement load +4323.83333 * Distance between rollers +8.25000E+005 * Sample thickness * Displacement load-1.65333E+005 * Sample thickness * Distance between rollers-1.70600E+005 * Displacement load * Distance between rollers +1.75556E+006 * Sample thickness^2 +1.05000E+005 * Displacement load^2-3120.00000 * Distance between rollers^2

Based on the above mentioned equation, the surface plots of correlation are generated. The following surface plot shows the influence of sample thickness and displacement load on residual stress. It is noticed that displacement load and sample thickness has significant influence on residual stress. The residual stress is increased when the sample thickness is less and displacement load is higher.
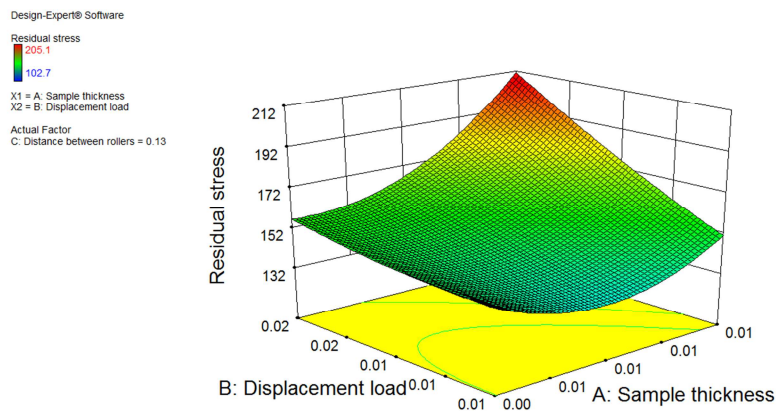

Figure 9. Residual stress on A and B.

The following surface plot shows the influence of sample thickness and distance between roller support on residual stress. The residual stress negligible influence when the distance between rollers varies at higher sample thickness. Whereas the residual stress increases significantly by changing the distance between roller at lower sample thickness.
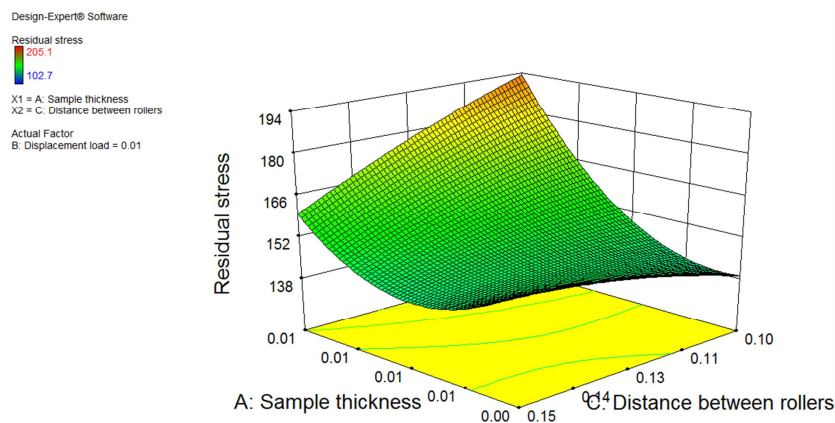

Figure 10. Residual stress on A and C.

The following surface plot shows the influence of distance between roller and displacement load on the residual stress. It is clear that the displacement load has negligible influence when distance between roller is higher whereas it has significant influence at short distances. The residual stress is increased when displacement load is higher with shorter roller distance.
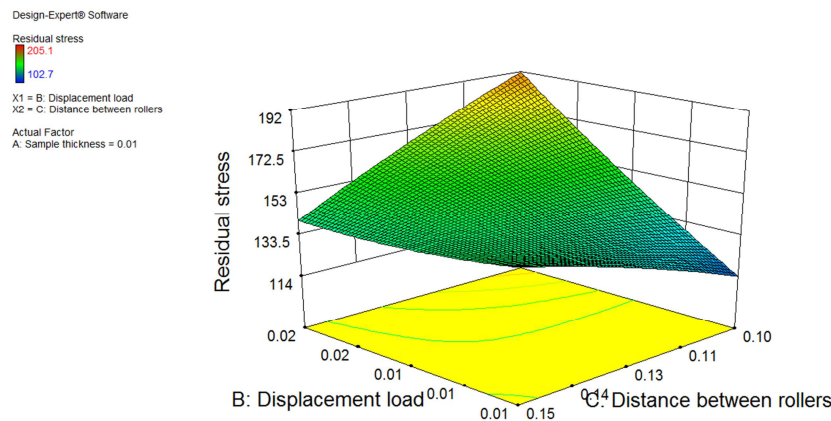

***Figure 11.** Residual stress on C and B.*

Based on the above surface plot the overall correlation can be understood that the residual stress is increased when sample thickness and displacement load is higher for shorter roller distances.

6. Conclusion

Based on the analysis the following conclusions are arrived,

- This study employed numerical simulations to understand the process in a effective way and mathematical correlations were developed.
- The spring back was increased for larger distance between rollers and smaller thickness whereas, component was induced higher residual stress as the thickness increases.
- It is understood that the thickness has significant role in the springback and residual stress formation. Further for the betterment of component strength these two parameter may be optimized and appropriate optimum parameters can be obtained.

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