Research Inventy: International Journal of Engineering And Science
Vol.7, Issue 6 (June 2017), PP -05-10
Issn (e): 2278-4721, Issn (p):2319-6483, www.researchinventy.com

Parametric Study in the Deep drawing of Finite Element Simulation of Super Duplex Stainless Steel Sheet

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ABSTRACT: *Deep drawing is one of the important sheet forming process used to make cup shaped components. In sheet metal forming, it is essential that the formed components are to be free from any defects such as undesired thinning, fracture, wrinkles or shape distortion etc. The die tryouts to achieve the defect free components will result in high cost of tooling and set up. Now a days numerical simulation is widely used to eliminate the costly trails. The accuracy of such simulations depends on the input parameters of the simulation. In this work, a parametric study was carriedout for the selection of appropriate input parameters for the finite element simulation such as material model, number of integration points and type of element that could ultimately lead to a reduction in lead time in the design of deep drawing process. The material considered for the study was Super duplex stainless steel sheet of grade (S32750). A commercially available finite element code Dynaform/Lsdyna was used in the simulation. The punch stem diameter, depth of drawing and the blank diameter were selected according to the benchmark specification given in Numisheet'2002.The results of experimentation and simulation were compared for the validity of simulation approach.*
Keywords: *Deep drawing, Dynaform, Finite element Simulation, Super duplex stainless steel*

I. Introduction

Deep drawing is one of the most common sheet metal forming processes which is widely used for mass production of cup shaped parts in automobile, petrochemical, and packaging industries. It is the processes of forming a flat blank in to hollow components without excessive wrinkling, thinning or fracture. Understanding the material behaviour during the processes is important and useful for accurate design of dies. In deep drawing, the quality of the formed parts is affected by the amount of the metal drawn into the die cavity.

A general trend in steel making is the development towards higher strength grades in order to achieve higher structural strength or to reduce the applied material thickness and in turn weight, e.g. in the automotive industry. Super duplex stainless steels are reasonably a new class of materials which exhibit high strength and excellent corrosion resistance. The material properties and the mechanical and physical behaviour of these new steel types are essential for processing and application, but the available knowledge is limited up to date. Therefore, systematic and comprehensive investigations are needed to thoroughly characterise these new steels for optimising and controlling its processing like sheet metal forming.

The experimental trial and error technique has now turned out to be very expensive and time consuming. Therefore, numerical simulations of sheet metal forming processes based on the finite element method (FEM) represent a powerful tool to predict, analyse and optimise the process behaviour of the sheet forming processes. The simulation requires the input of suitable material models describing the mechanical properties. Available material models that have proven to be valid for a wide range of steel types need to be verified for this steel as its behaviour can differ significantly.

II. Parametric Study in Finite Element Analysis of Deep Drawing

The conditions for using methods of forming processes in finite element modeling are not only efficient computers but also the knowledge of the parameters which are used as input to the finite element modeling . The accuracy of simulations depends on the numerical parameters such as element type, mesh size and the number of through-thickness integration-points, as well as the constitutive model (mathematical descriptions of the material behavior) that governs the behaviour of the deformable sheet. Therefore, the choice of input values of the simulation parameters are to be carefully made to get accurate simulation results. In this study, it was decided to evaluate and choose some of the important input parameters such as material model (MM) [1], type of element (TE) [2] and number of integration points (NIP) [3] before evaluating the process and tooling parameters in the deep drawing process of super duplex stainless steel sheet material. Deep drawing simulations were carriedout as per the guidelines of benchmark specification given in Numisheet, 2002 [4]. The same guidelines - tool dimensions, blank dimensions, depth of drawing etc. were followed for carrying out real time experimentation. The comparison of the simulation results with experimental values leads to the selection of appropriate input parameters for further finite element analysis of deep drawing process.

2.1 Material Model

The material constitutive models such as Barlat'89 and Hill'48 are normally preferred in sheet metal simulation in industrial atmosphere due to their simplicity and cheaper cost of simulation. These two constitutive models have been implemented by material models MAT 36 and MAT 37 respectively in the commercially available software Dynaform/Lsdyna. These models can be implemented to new materials very quickly with fewer data. In this investigation, these two material models have been considered for their suitability in providing accurate simulation results of modelling the Super duplex stainless steel sheet material.

2.1.1 Material Model - MAT 36 (Barlat'89)

This criterion incorporates the effect of both normal and planar anisotropy in the yielding behaviour of the material [5].This model was developed by Barlat and Lian [6] for modeling the sheets with anisotropic materials under plane strain conditions. This material model allows the use of Lankford parameter in 0°, 45° and 90° to the rolling direction for the defining of anisotropy.

2.1.2 Material Model - MAT 37 (Hill'48)

Hill [7] proposed various anisotropic yield functions among which the 1948 version is still commonly used mainly due to its simplicity and user friendliness. The metallic sheets exhibit an anisotropic behaviour characteristic of the rolling process. Hence, Hill proposed an anisotropic yield criterion, considering that the material has an anisotropic behaviour along three orthogonal symmetry planes (orthotropic behaviour).

2.2 Types of Element

The selection of an appropriate element type is also very important for accurate modeling using finite element analysis. The type of element to be used in the analysis influences the exactness and accuracy of the results to a great extent. [8], Depending on the problem and the geometry of the sheet metal part, different types of elements can be used to discretize the blank i.e. 2D plane strain, shell, solid or solid-shell. Shell elements are commonly used in simulations of sheet metal forming.

Use of shell element gives more number of degrees of freedom to capture accurate stress distribution including in- plane and out-plane deformation. At the same time, it takes a substantial amount of computational time and computer space for its 3-D calculation with integration in the thickness direction. Thin shell elements are normally used to describe the deformable blank. In this study, the most commonly used Hughes-Liu (HL) shell element [9] and Belytschko-Lin-Tsay (BT) shell element and Belytschko-Wong-Chiang shell element were considered.

2.3 Number of Integration Points

Finite Element Analysis (FEA) can produce an enormous amount of data as output. Solution variables such as stress and strain are computed throughout an analysis for each increment and at each location within the model. These solution variables are computed at what are called "integration points". Larger NIP can more accurately reproduce continuous stress distribution, and also the post forming bending moment, but at the expense of increased computation time, as reported by several researchers. Although the choice of number of integration point is still an open issue in the simulation, the choice for this study was made based on the literatures. It has been stated that the through thickness variations are well captured using five or more through thickness integration points [10] And therefore, the maximum number of integration points for this study has been chosen to be 11.

III. Planning of Simulation Runs

In order to carryout simulation runs, design of experiments approach was used. Design of Experiments (DOE) is a formal structured technique for studying any situation that involves a response that varies as a function of one or more independent variables. DOE can provide answers to specific questions about behaviour of a system, using an optimum number of experimental observations.

Table 1 Parameters and their Levels

Parameter	Symbol	Levels		
		1	2	3
Number of Integration Points	NIP	5	8	11
Type of Element	TE	BL	BW	HL
Material Model	MM	M36		M37

Table 2 Design matrix in actual and coded values

Exp. Run	Coded value			Actual value		
	NIP	TE	MM	NIP	TE	MM

1	1	2	2	5	BW	M37
2	1	3	1	5	HL	M36
3	3	1	2	11	BL	M37
4	2	1	1	8	BL	M36
5	1	2	1	5	BW	M36
6	1	3	2	5	HL	M37
7	1	1	1	5	BL	M36
8	3	3	2	11	HL	M37
9	1	1	2	5	BL	M37
10	3	1	1	11	BL	M36
11	2	3	1	8	HL	M36
12	2	3	2	8	HL	M37
13	3	2	2	11	BW	M37
14	3	2	1	11	BW	M36
15	2	2	1	8	BW	M36
16	2	2	2	8	BW	M37
17	3	3	1	11	HL	M36
18	2	1	2	8	BL	M37

Table 1 shows the three input parameters and their levels selected for the study. Among which one is a continuous factor (NIP) and other two (TE & MM) are categorical factors. According to the central composite design, eighteen simulation runs are to be carriedout. Table 2 shows the design matrix in coded and actual values. Only one quarter of the deep drawing model was created due to symmetrical nature of the cup using commercially available Dynaform/Lsdyna software. Fig. 1 shows the model with punch, Die, blank holder and the blank. The properties of the selected sheet material were determined using appropriate test procedures and shown in Table 3 and provided as input to the finite element modeling.

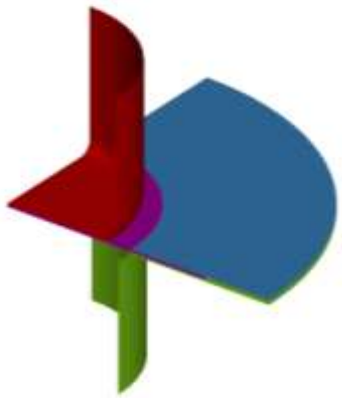

Fig. 1 Finite element model of deep drawing process

Table 3 Properties of Super Duplex Stainless Steel Sheet Material

Property	**Value**
Ultimate Tensile Strength	841 MPa
Tensile Yield Strength	673 MPa
Elongation (%)	30
Anisotropy factor, r_0	0.40
Anisotropy factor, r_{45}	0.92
Anisotropy factor, r_{90}	0.78
Normal anisotropy $\bar{r}$	0.755
Strain hardening exponent, n	0.30
Strength coefficient, K	1753 MPa

Eighteen deep drawing simulation runs were carriedout with varying simulation parameters (material model, type of element, and number of integration points) as per the design matrix given in Table 2. Thickness was measured at sixteen points along the edge of the cup of each simulation run and the values are given in Table 4.

An important requirement and objective in order to obtain an increased quality of the drawn parts necessitates to control or avoid the sheet thickness variation and to maintain a uniform sheet thickness to the extent possible on all part zones during sheet metal deep drawing [11]. It is essential to obtain thickness values with minimum deviation from the nominal sheet thickness. i.e. chosen sheet thickness of 1 mm. Accordingly, the objective function (ϕ) for comparing the simulated and experimental result was chosen and given in equation (1).

$$\phi = (t_1 - t_0)^2 + (t_2 - t_0)^2 + (t_3 - t_0)^2 + \dots\dots\dots (t_{16} - t_0)^2 \quad (1)$$

Where t_1 *to* t_{16} are thickness values measured at sixteen points chosen along the cup section and t_0 is the original thickness of the sheet material, 1 mm.

Table 4. Thickness values

Points	Thickness values (Simulated) in mm								
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
1	0.9159	0.9833	0.9691	0.9343	0.9335	0.992	0.9328	0.9923	0.9693
2	1.1787	1.3012	1.1757	1.2986	1.2998	1.176	1.2967	1.176	1.1766
3	1.1726	1.2559	1.1672	1.2538	1.2547	1.168	1.2501	1.1656	1.1708
4	1.1384	1.1975	1.134	1.1942	1.1975	1.136	1.1929	1.1371	1.1388
5	1.0642	1.1014	1.0609	1.0987	1.0968	1.056	1.0992	1.0634	1.0583
6	1.0144	1.0363	1.0137	1.0367	1.0351	1.009	1.0336	1.0111	1.0138
7	0.9729	0.9959	0.9683	0.9951	0.9953	0.97	0.9947	0.9693	0.9716
8	0.971	0.9576	0.9689	0.956	0.9572	0.969	0.9565	0.9693	0.9697
9	0.9554	0.9387	0.9466	0.9393	0.9385	0.949	0.937	0.9466	0.949
10	0.9785	0.9452	0.9731	0.9451	0.9451	0.973	0.9439	0.9733	0.9734
11	0.9813	0.943	0.9764	0.9429	0.943	0.976	0.9418	0.9764	0.9763
12	0.9812	0.9408	0.976	0.9451	0.9406	0.976	0.9395	0.9761	0.976
13	0.9801	0.9384	0.9746	0.9379	0.9385	0.974	0.9367	0.9745	0.9745
14	0.9797	0.935	0.9746	0.9349	0.9351	0.974	0.9343	0.9741	0.9742
15	0.9773	0.9327	0.972	0.9287	0.9336	0.972	0.9322	0.9725	0.9709
16	0.9703	0.9561	0.9637	0.9287	0.9284	0.978	0.9282	0.9789	0.964
Objective Function (ϕ)									
	0.0992	0.2369	0.0917	0.2399	0.2417	0.0899	0.2374	0.0905	0.0938

Points	Thickness values (Simulated) in mm								
	Run 10	Run 11	Run 12	Run 13	Run 14	Run 15	Run 16	Run 17	Run 18
1	0.9329	0.9833	0.9924	0.9689	0.9283	0.9324	0.9632	0.9832	0.9637
2	1.3011	1.3019	1.1757	1.1781	1.2891	1.2975	1.1738	1.3014	1.1731
3	1.2554	1.2563	1.1693	1.1677	1.2396	1.2501	1.1629	1.2558	1.1628
4	1.1972	1.1969	1.1378	1.1377	1.1799	1.1928	1.1372	1.1973	1.1348
5	1.1047	1.1049	1.0603	1.0604	1.0876	1.1008	1.0596	1.104	1.0569
6	1.0383	1.0392	1.0156	1.0116	1.0279	1.0353	1.0092	1.0383	1.0058
7	0.9958	0.9957	0.9714	0.9693	0.9883	0.9946	0.9682	0.9959	0.967
8	0.9559	0.9562	0.9692	0.9695	0.9499	0.9553	0.9682	0.9557	0.9672
9	0.9399	0.9396	0.9457	0.9463	0.9329	0.9389	0.9421	0.9331	0.942
10	0.9457	0.9455	0.9732	0.9732	0.9389	0.9443	0.9685	0.9352	0.9683
11	0.9435	0.9432	0.9761	0.9763	0.937	0.9421	0.9717	0.9384	0.9715
12	0.9409	0.9407	0.9756	0.9759	0.9345	0.9397	0.9714	0.9407	0.9714
13	0.9302	0.9385	0.9743	0.9744	0.9318	0.9369	0.9698	0.9433	0.97
14	0.9352	0.9352	0.9741	0.974	0.9295	0.9343	0.9699	0.9457	0.9696
15	0.9327	0.9327	0.9715	0.9719	0.9267	0.9319	0.9679	0.9399	0.9673
16	0.9281	0.9556	0.9796	0.961	0.9222	0.9274	0.9589	0.9562	0.9589
Objective Function (ϕ)									
	0.2457	0.2382	0.0916	0.0938	0.2271	0.2383	0.0931	0.2374	0.0920

IV. Experimentation

Punches and dies were manufactured to the specified radii and the deep drawing experiments were conducted for which the guidelines of bench mark test provided in the Numisheet'2002 were adopted. Two sheet blanks were cut from the Super Duplex Stainless Steel sheet material. Two cups were drawn to a depth of 40 mm and the photograph cups are shown in Fig. 2.

Fig. 2 Formed Cups

V. Thickness Measurements

The drawn cups were sectioned at the middle using wire cut EDM process in order to cut the cup without introducing any stresses during cutting and the thickness was measured at sixteen from the centre of the cup to the edge of the flange. Thickness was measured using pointed micrometer with a least count of 001. mm. Values were obtained for two specimens and the values were averaged. Based on the measured thickness values, the objective Function (ϕ) were calculated are given in Table 5.

VI. Results and Discussion

The results of the simulation runs and experimentation were compared to identify the suitable parameter setting of finite element simulation. The absolute difference of objective function of each simulation run with experimental result was calculated and given in Table 5. It has been found that the experimental result was in closest agreement with simulation run No. 14. i.e., the absolute difference of deviation of objective functions of experimentation and simulation run no 14 is least (Fig. 3). And therefore, it has been inferred that the modeling parameters of Run No. 14 are the most realistic representation of the experimental results. Accordingly, the modeling parameters such as MAT 36 (material model), Belytschko-Wong-Chiang (Element type) and 11 (Number of integration Points) have been chosen for further study of the finite element simulation and analysis of deep drawing process of the super duplex stainless steel sheet material. The reason for the suitability of the material model MAT 36 could be attributed as follows. MAT 36 material model which implements Barlat'89 yield criteria can be regarded as an instantaneous plastic potential of the materials under consideration at least under linear loading paths and therefore it is effective in the prediction of plastic deformation of SDSS steel sheet materials. And also, the adoption of only the normal anisotropy by the MAT 37 might not be sufficient to capture the deformation behavior of the super duplex steel sheet. Belytschko-Wong-Chiang element type is able to predict even small strains and this element type treats the warpage configurations properly. When a material undergoes plastic deformations there appear points of discontinuity in the stress distribution and the number of the integration points needed to obtain accurate results increases. Hence NIP of 5 is not sufficient here. At the same time, very high number of integration points, 11 might make the model in exact due to over stiffness. These reasons make the suitable NIP's to 8 in this simulation.

Table 5 Absolute Difference of Objective Function

Run No.	ϕ Simulated	ϕ Experimental	Deviation	Run No.	ϕ	ϕ Experimental	Deviation
1	0.0992		0.1269	**10**	0.2457		0.0195
2	0.2369		0.0108	**11**	0.2382		0.0121
3	0.0917		0.1344	**12**	0.0916		0.1345
4	0.2399		0.0138	**13**	0.0938		0.1323
5	0.2417	0.2261	0.0156	**14**	0.2271	0.2261	**0.0010**
6	0.0899		0.1362	**15**	0.2383		0.0121
7	0.2374		0.0113	**16**	0.0931		0.1331
8	0.0905		0.1356	**17**	0.2374		0.0113
9	0.0938		0.1324	**18**	0.0920		0.1342

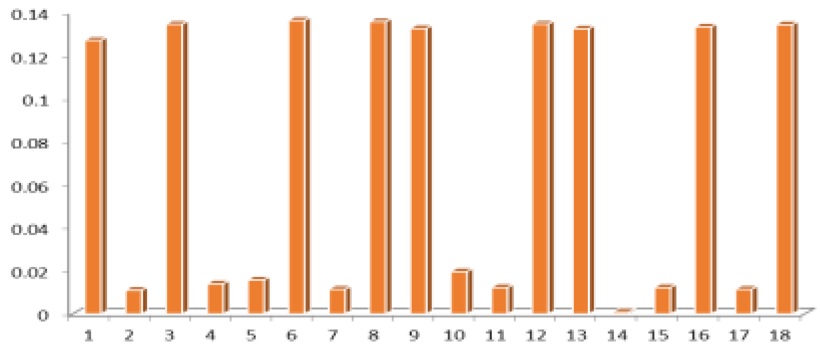

Fig. 3 Plot of Deviations of Objective Function

VII. Conclusion

The results of the simulation runs and experimentation in the deep drawing process of super duplex stainless steel were compared to identify the suitable parameter setting of finite element simulation. Based on the absolute difference of objective function of each simulation run with experimental result, it has been found that the modeling parameters of Run No. 14 are the most realistic representation of the experimental results. Accordingly, the modeling parameters such as MAT 36 (material model), Belytschko-Wong-Chiang (Element type) and 11 (Number of integration Points) can be chosen for further study of the finite element simulation and analysis of deep drawing process of the super duplex stainless steel sheet material.

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