Parametric Optimization of Warm Deep Drawing Process of SS 304 Cylindrical Cups

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Abstract- The present work is comprehensive parametric optimization of the warm deep drawing process of 304 stainless steel. The warm deep drawing process is a crucial metal forming technique that leverages elevated temperatures to enhance the material's formability and reduce defect occurrence. This study systematically investigates the influence of various process parameters, including sheet thickness, temperature, coefficient of friction, and strain rate, on the quality of the final product in order. Using the Taguchi method for design of experiments and Finite Element Analysis (FEA) for simulation, the research aims to determine the optimal settings for these parameters. Every parameter played its part in responses. All the factors had similar impact on the cups designed. The strain based FLDs are prepared to study the strain levels in the process The optimized cup was found to be the trail 8 cup with 1 mm, 300°C, 0.02 and 1000s^{-1}.

Keywords- Sheet thickness, Coefficient of Friction, Damage, SS 304, Cylindrical cups

I. INTRODUCTION

Deep drawing is a sheet metal forming technique where a flat blank is constrained by a blank holder while the central portion is pushed into a die to create a deep, cuplike shape. There are many process parameters governing the quality of cups and some of the parameters are studied. R. Padmanabhan et al., 2007 applied a combination of the Finite Element Method (FEM) and the Taguchi technique to assess the impact of critical process variables, such as die radius, blank holder force, and friction coefficient, in the deep drawing process. F. Ayari et al., 2009 performed a parametric study on the deep drawing process using a Finite Element Method (FEM) model developed with ABAQUS/Explicit standard code. The study's experimental findings were compared with the FEM model results, highlighting the critical role of these parameters in the deep drawing process. Kopanathi Gowtham et al., 2021 investigated the impact of varying the die radius on several parameters, including effective stress, effective strain, maximum principal stress, maximum principal strain, damage value, and the required load. Their study concluded that the die radius is a crucial design parameter. A. C. Reddy et al., 2016 examined the deep drawing capability of Nickel 201 cylindrical cups. They found that punch velocity and strain rate were the primary factors affecting the process, resulting in increased effective stress at higher punch velocities. Bhargavi et al., 2020 optimized the process parameters for the cold deep drawing of Inconel 600 conical cups. They found out with thicker sheets, there was more raw material that could be drawn and formed into taller cups. Nithin Sai et al. 2020 conducted simulations to optimize Nickel 201 conical cups. They observed that a higher coefficient of friction resulted in a greater surface expansion ratio. These findings provide valuable guidance for optimizing the deep drawing process of Nickel 201 conical cups, allowing manufacturers to achieve desired cup characteristics by adjusting the coefficient of friction and blank thickness. Omalayo et al., 2022 discussed the overall process and considerations to be taken for the deep drawing process. He provided a comprehensive paper on the technicalities of the process and the preventive measures to produce cups. Zainab H. Mohsein et al., 2024 conducted research to fabricate pentacal cups of low carbon steel, made use of ANSYS to simulate the process and found out the differences in produced cups via three different processes.

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II. MATERIAL AND METHODOLOGY

Stainless steel 304 is the material equipped for producing cylindrical deep drawn cups.

SS 304, also known as 18/8 stainless steel, is a widely used austenitic stainless-steel alloy due to its exceptional corrosion resistance, formability, and weldability. The alloy contains 18% chromium and 8% nickel, which provides superior corrosion resistance compared to other stainless-steel grades.

Table 1. Process parameters and levels

Factors		Level 1	Level 2	Level 3
Thickness (mm)	A	0.5	0.75	1
Temperature (°C)	B	100	300	500
Coefficient of friction (μ)	C	0.02	0.04	0.08
Strain rate (s^{-1})	D	100.00	500.00	1000.00

Table 2. L9 Orthogonal Array

Trial	A	B	C	D
1	0.5	100	0.02	100
2	0.5	300	0.04	500
3	0.5	500	0.08	1000
4	0.75	100	0.04	1000
5	0.75	300	0.08	100
6	0.75	500	0.02	1000
7	1	100	0.08	500
8	1	300	0.02	1000
9	1	500	0.04	100

2.1 FORMULAE FOR DEEP DRAWING CYLINDRICAL CUPS

The blank size is determined by equalling the surface area of the finished drawn cup with the area of the blank.

The diameter of the blank is given by:

$$D = \sqrt{(d^2 + 4dh)} \quad \text{for d/r > 20} \quad (1)$$

$$D = \sqrt{(d^2 + 4dh) - 0.5r} \quad \text{for 15< d/r < 20} \quad (2)$$

$$D = \sqrt{(d^2 + 4dh)} - r \quad \text{for 10 < d/r < 15} \quad (3)$$

$$D = \sqrt{(d - 2r)^2 + 4d(h - r) + 2\pi r(d - 0.7r)} \quad \text{for d/r < 0} \quad (4)$$

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where d is the mean diameter of the cup (mm), h is the height of cup (mm) and r is the corner radius of the die (mm).

The force for drawing relies on the yield strength of the material σ_y, diameter and thickness of the cup:

$$F_d = \pi dt(D/d - 0.6)\sigma_y$$

where D is the diameter of the blank before operation (mm), d is the diameter of the cup upon drawing (mm), t is the cup thickness (mm) and σ_y is the yield strength of the blank material (N/mm^2).

The drawing punches' corner radius exceeding three times the blank thickness (t). However, the punch radius should not exceed one fourth the cup diameter for the good flow and material distribution without failure.

$$3t < \text{Punch Radius} < d/4 \quad (6)$$

For smooth flow of the material the die edge radius is set preferably four to six times the blank thickness but not less than three times the sheet thickness because lesser radius would stop material flow while excess radius the pressure area is between the blank and the blank holder is decreased. The corner radius of the die is calculated from the following equation:

$$r = 0.8\sqrt{(D-d)t} \quad (7)$$

The drawing ratio is roughly given as:

$$D.R = D/d \quad (8)$$

The material flow in drawing might produce flange thickening and thinning of walls of the cup is normal. The space for drawing is kept bigger than the sheet thickness. This space is called die clearance.

$$c = t \pm \mu\sqrt{(10t)} \quad (9)$$

2.2 FINITE ELEMENT ANALYSIS

Using DE FORM 3D software, the simulation of the deep drawing was run. The top die and bottom dies are calculated per the formula and are modelled in the software. The blank(workpiece) is made with the diameter D from eq. (1) and is meshed with tetrahedral elements. For every thickness, the corner radii are changed and so is the slight variation in the die's radius. Every combination in L9 array is simulated and results are extracted from the post processing window of the software.

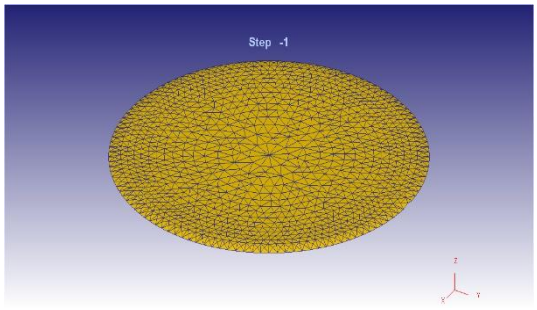

Fig 1. Meshed sheet metal

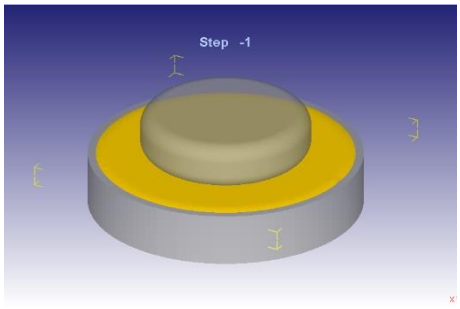

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Fig 2. Die and sheet metal as a couple

The number of elements in the blank: 7089

The number of nodes in the blank: 2382

III. RESULTS

3.1 Influence of Factors on Effective Stress

Using ANOVA statistic technique and the appropriate formula below table is tabulated. The Fisher's test column ascertains the parameters (A, B, C, and D) at 90% confidence level for the variation. The percentage contribution shows thickness of sheet attributes to 6.96% of variation, coefficient of friction strain rate held no significance. The contribution of temperature is 91.36%.

Table 3. ANOVA table with Effective Stress as response

Factor	S1	S2	S3	SS	v	V	F	P
A	313.30	294.30	289.94	102.85	2	102.85	8570.83	6.96
B	346.00	295.28	256.26	1349.82	2	1349.82	112485.00	91.36
C	294.98	298.46	304.10	14.12	2	14.12	1176.67	0.96
D	297.26	296.50	303.78	10.67	2	10.67	889.17	0.72
e				0.01	8	0.00	0.00	0.00
T	1251.54	1184.54	1154.08	1477.47	16			100.00

Where SS is the sum of square, v is the degrees of freedom, V is the variance, F is the Fisher's ratio, P is the percentage of contribution and T is the sum squares due to total variation.

There is larger effect of temperature on the effective stress is evident from the ANOVA table with the highest contribution of 91% and there is small effect of other thickness on the effective stress. The other 2 factors have no impact on the effective stress.

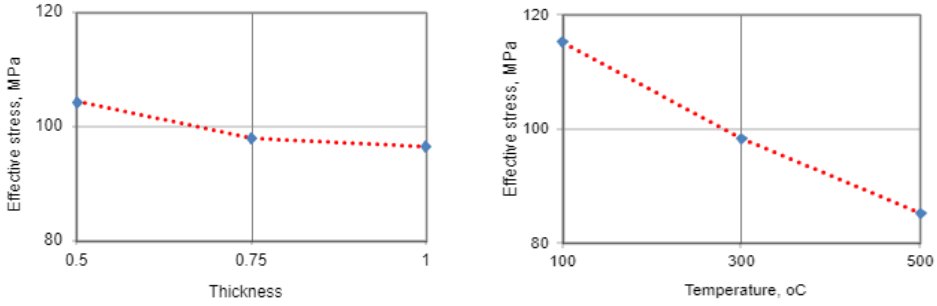
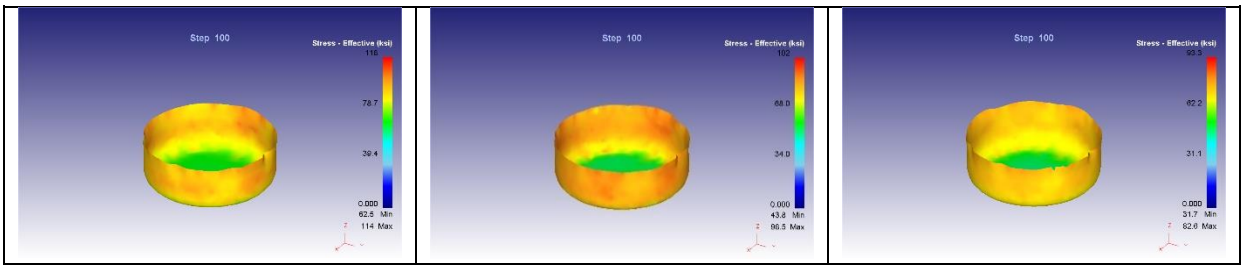


Fig 3. Variation of parameters with Effective stress

With increase in temperature the stress produced is decreasing and the load required to deform into cups is also less. The temperature increase resulted in improved formability of sheet metal. The thickness of the material which is not that significant factor with low percentage of contribution but the thickness of 0.5 mm had more effective stress induced.



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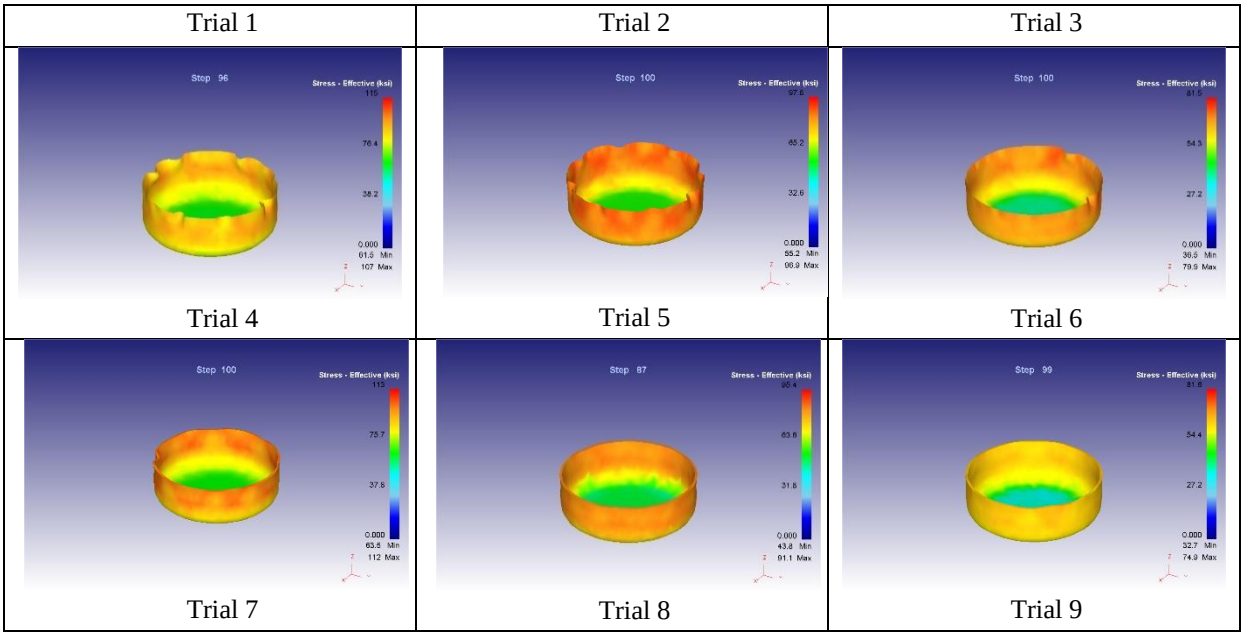


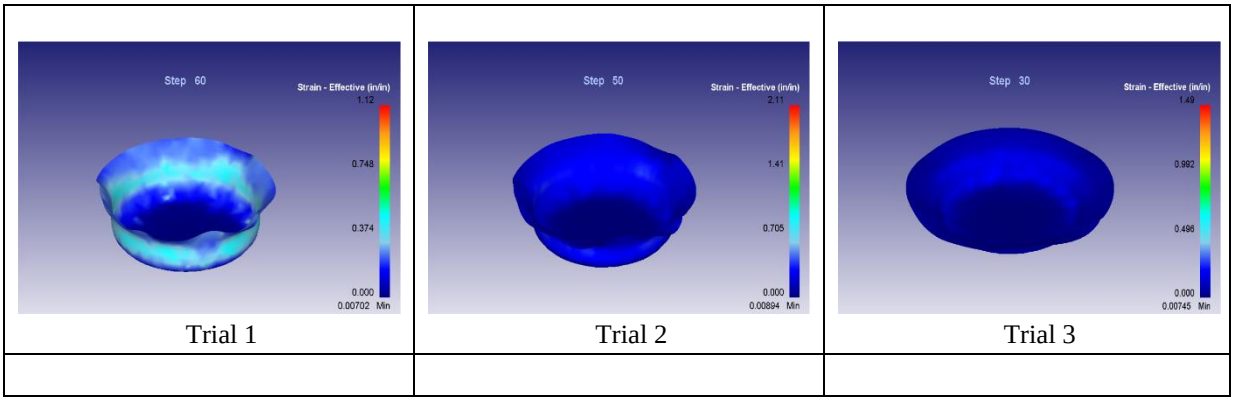
Fig 4. Effective stress of cups

3.2 Influence of Factors on Effective strain

The ANOVA test for cup's effective strain is given in table. The Fisher's test column ascertains the parameters (A, B, C, and D) accepted at 90% confidence level for the variation. The percentage contribution shows thickness of sheet attributes to 65.09% of variation, coefficient of friction attributes to 10.58% of variation and strain rate holds 24.08% of variation. The contribution of temperature is negligible.

Table 4. ANOVA table for Effective Strain as response

Factor	S1	S2	S3	SS	v	V	F	P
A	46.9	52.6	24.55	146.53	2	146.53	732.65	65.09
B	41.7	41.89	40.46	0.40	2	0.4	2.00	0.16
C	36.09	47.86	40.1	23.87	2	23.87	119.35	10.58
D	32.36	50.4	41.29	54.25	2	54.25	271.25	24.08
e				0.20	8	0.05	0.25	0.09
T	157.05	192.75	146.4	225.05	16			100



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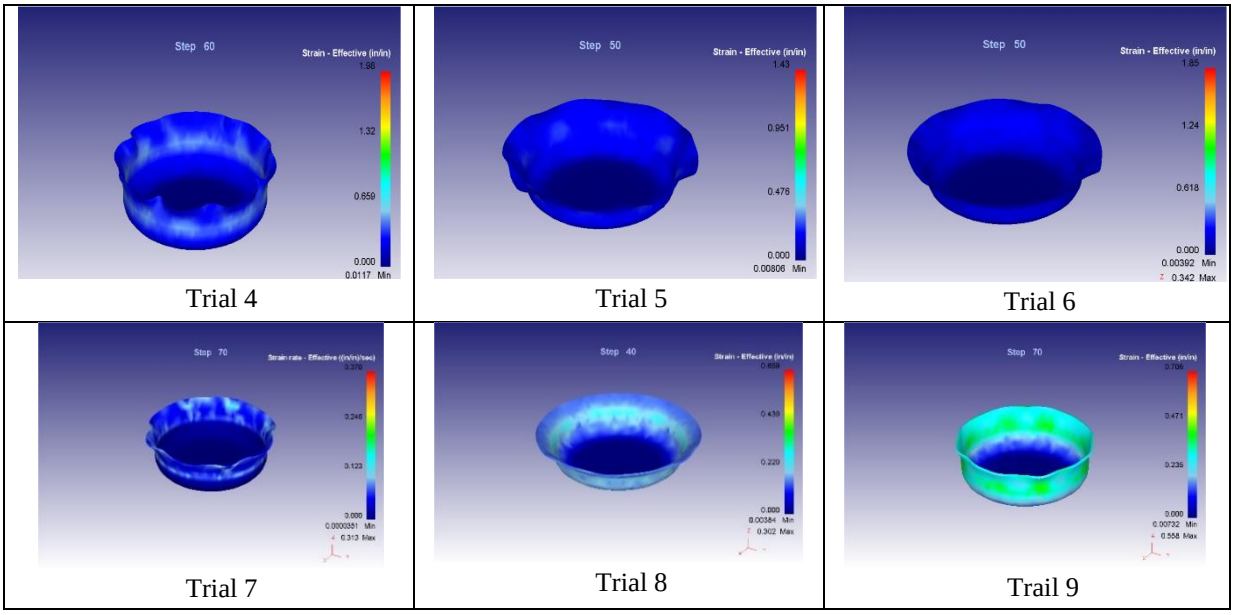

Fig 5. Effective strain of cups

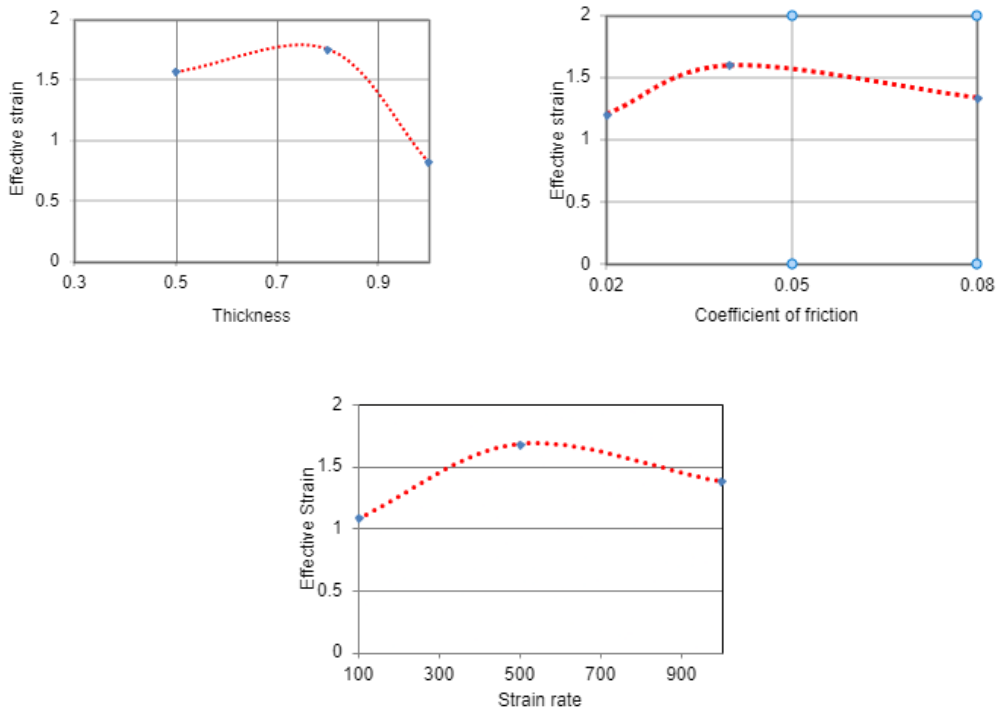

Fig 6. Variation of factors with effective strain

Peculiarity in the graph trends slightly increasing at low thickness and decreasing at higher thicknesses. All the parameters studied are seen not to follow conventional trend. At lower thickness the deformation is easy because of flow of metal. At 0.5mm thickness blank adapts to the load and quickly deforms into the shape with less strain. But at 0.75mm thickness, the blank resists the deformation resulting in more effective strain. At 1mm thickness the material is much more resistant and strain doesn't go beyond the limit. The effective strain was found to be high for μ=0.04 and less at remaining levels. The strain rate $500s^{-1}$attributed to highest strain while the fast and slow deformation maintained low strain.

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3.3 Influence of Factors on Surface expansion ratio of the cup

The ANOVA summary of cup damage is given in table. The Fisher's test column ascertains all the parameters (A, B, C, and D) accepted at 90% confidence level influencing the variation. The percent contribution indicates that thickness of sheet gives 26.46% of variation, coefficient of friction contributes 10.94% of variation and strain rate controls 22.39% of variation. The influence of temperature is of 39.69%.

Table 5. ANOVA table for Surface expansion ratio as response

Factor	S1	S2	S3	SS	v	V	F	P
A	34	36.3	36	1.04	2	1.04	52.00	26.46
B	33.7	36	36.6	1.56	2	1.56	78.00	39.69
C	34.5	35.9	35.9	0.43	2	0.43	21.50	10.94
D	34.1	36.1	36.1	0.88	2	0.88	44.00	22.39
e				0.02	8	0	0.00	0.52
T	136.3	144.3	144.6	3.93	16			100

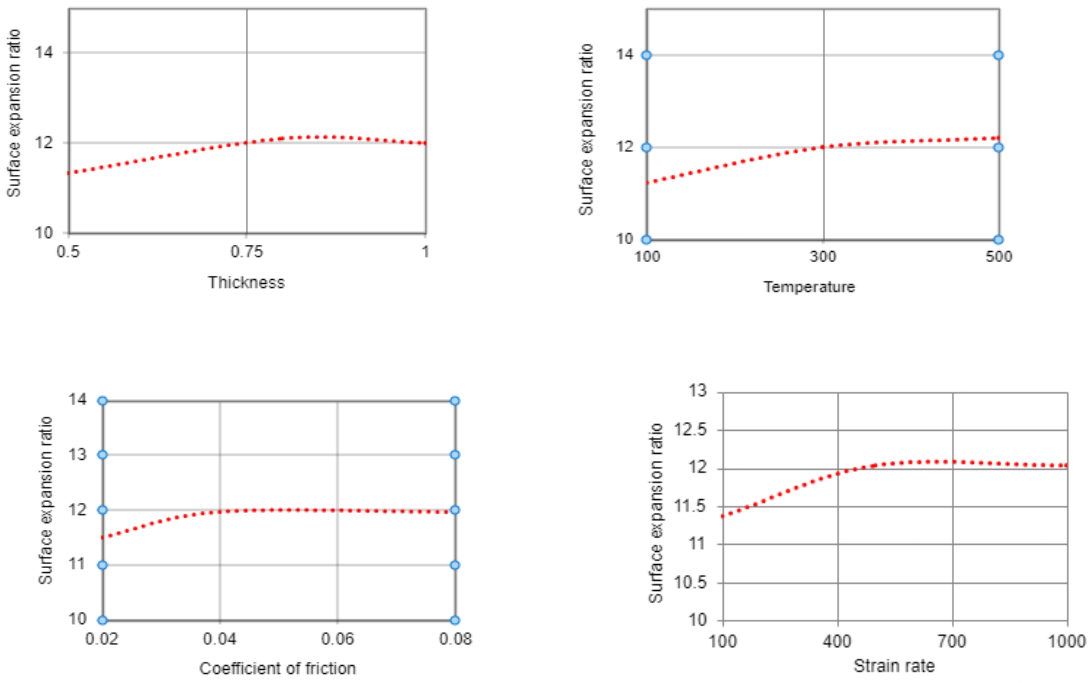

Fig 7. Variation of factors with Surface expansion ratio

There is increase in surface expansion ratio with increasing thickness surface expansion ratio increases with increasing temperature in the above graph. The temperature of the blank and heat transfer between the dies' plays a role in the surface expansion. More the thickness, more is the resistance to surface expansion. Coefficient of friction is also proportional to the surface expansion. Fast deformation results in more expansion and steady deformation keeps the material uniform and resulting in less surface expansion.

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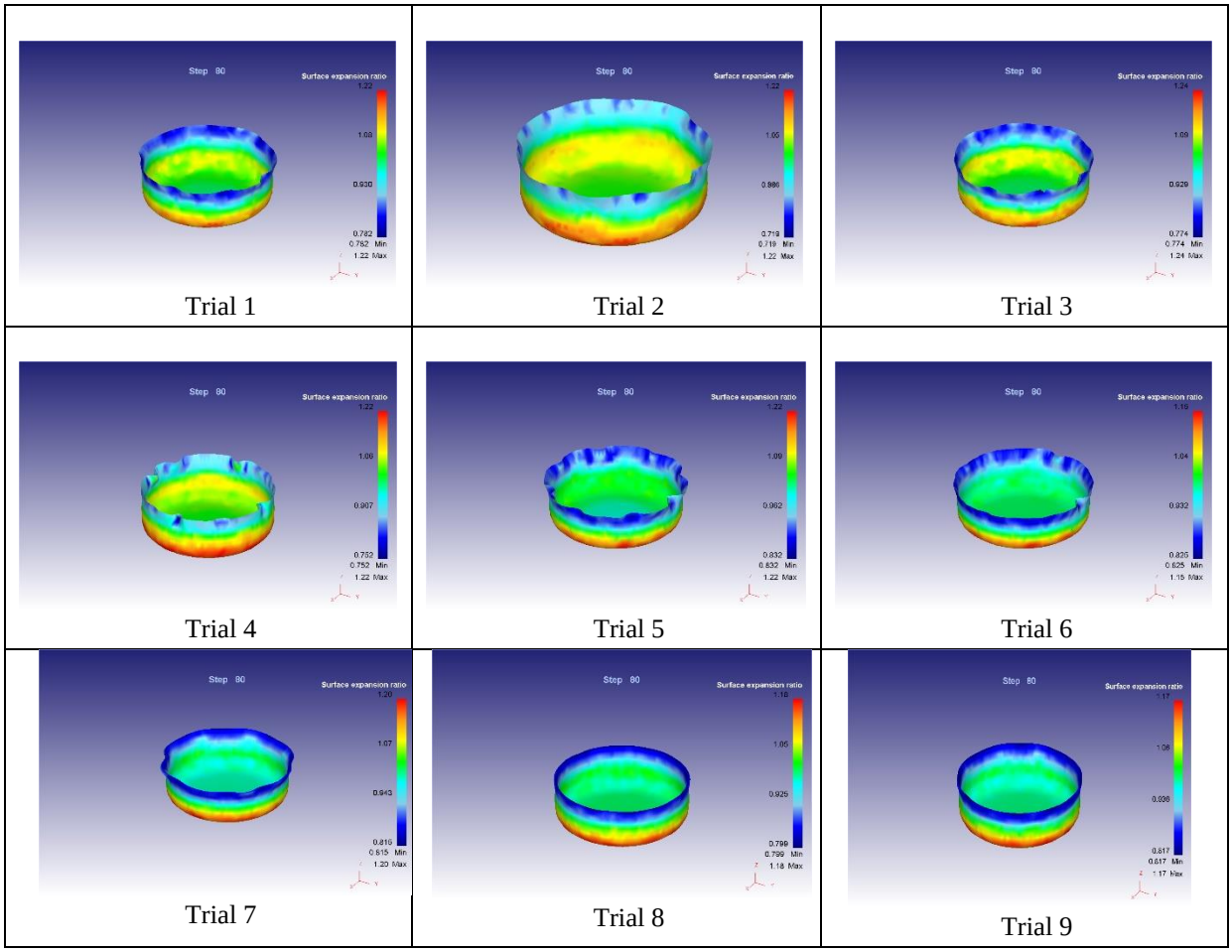

Fig 8. Surface expansion ratios of the cups

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3.4 Influence of Factors on Damage of the cup

The ANOVA summary of cup damage is given in table. The Fisher's test column ascertains all the parameters (A, B, C, and D) accepted at 90% confidence level influencing the variation. The percent contribution indicates that thickness of sheet gives 63.54% of variation, coefficient of friction contributes 2.99% of variation and strain rate controls 46.63% of variation. The influence of temperature is of 16.2%.

Table 6. ANOVA table for Damage as response

Factor	S1	S2	S3	SS	v	V	F	P
A	4.177	2.314	1.216	1.49	2	1.49	99.43	63.54
B	2.952	1.691	3.064	0.38	2	0.38	25.36	16.2
C	2.448	2.327	2.932	0.07	2	0.07	4.67	2.99
D	2.27	1.993	3.444	0.39	2	0.39	26.03	16.63
e				0.014985	8	0	0.00	0.64
T	11.847	8.325	10.656	2.344985	8			100

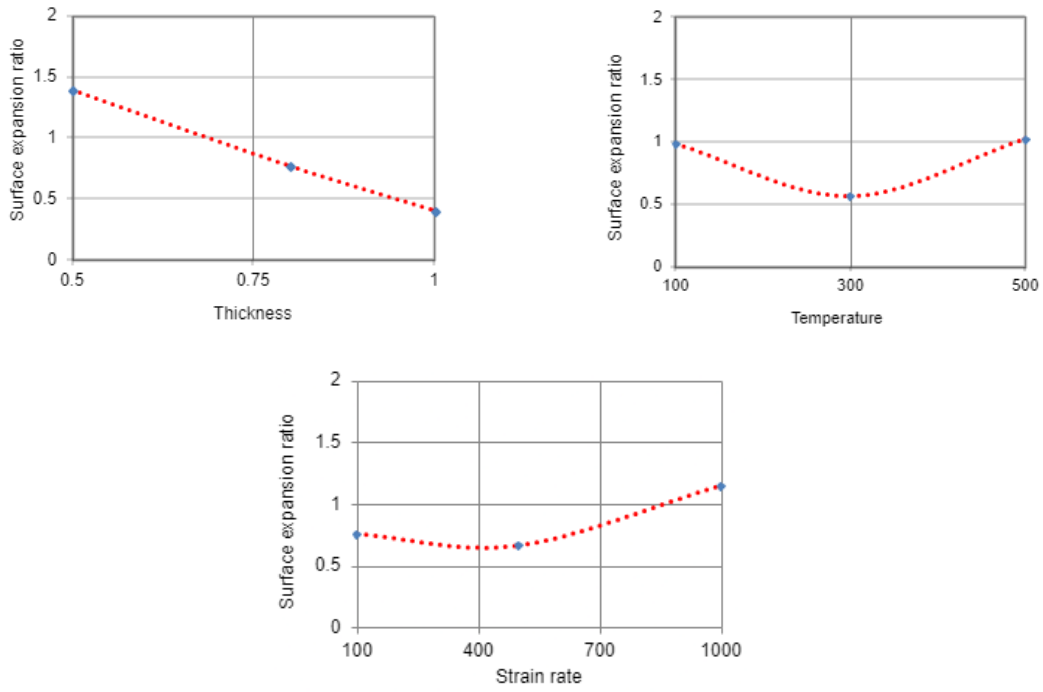

Fig 9. Variation of process parameters with damage

The damage is decreasing with increasing thickness which suggests the susceptibility of larger thicknesses to the damage produced. Quick deformation shown more damage to the cups than the slowly controlled deformations, lower strain rate is helpful to control damage. The damage is varying within three temperatures which attributes to the heat transfer that occurs between the dies and blank sheet. The die temperature was set near to the 300°C, hence the damage is low at this temperature.

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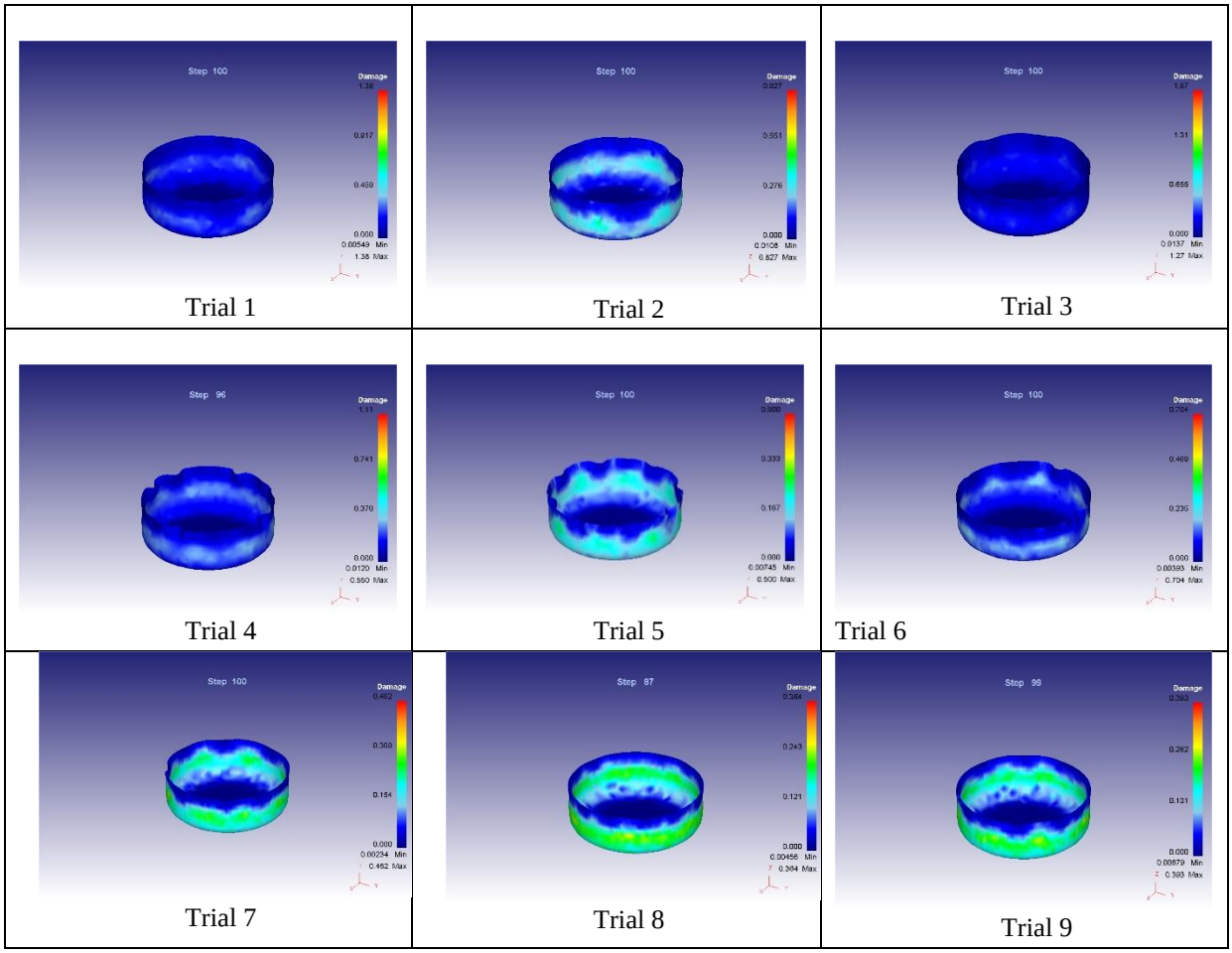

Fig 10. Damage of the cups

3.5 Formability Limit Diagram

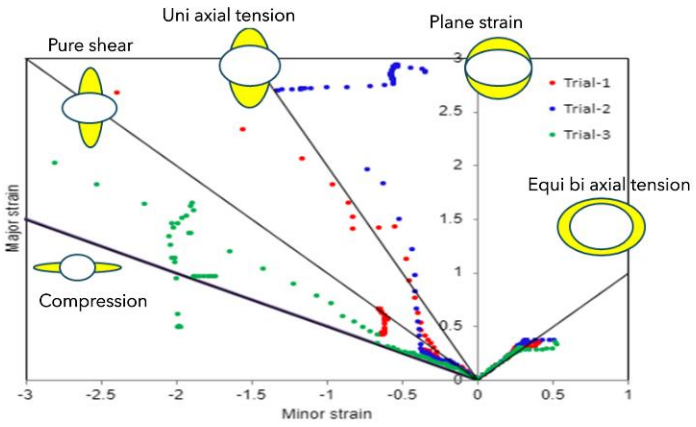

Fig 11(a). FLD of trails 1,2&3 with 0.5mm thickness

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The diagram has some elements having strains beyond the desired limit that is at the compression region of the curve and also many point scatterings at the top of the diagram which are responsible for the wrinkling and defects in the trails 1,2 and 3. All the three had strain points beyond the limit and that led to some damage in the cups.

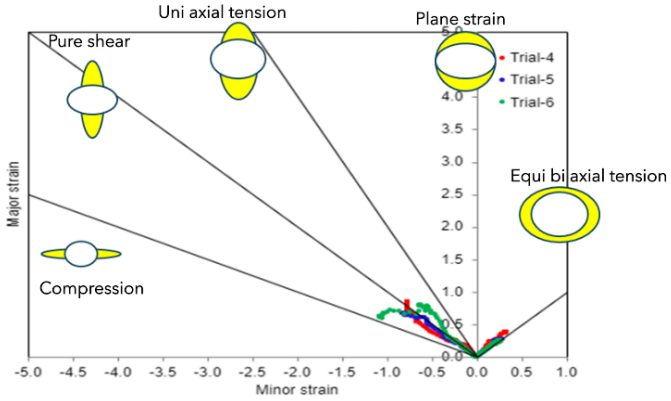

Fig 11(b). FLD of trials 4,5&6 with 0.75 mm thickness

The strain levels of the FLD of the trials 4,5&6 is having cluster of the strain value points in the diagram which pertains to the less damage and wrinkles than the first trials. However, there is some tendency towards the compression and non-linearity in the points that resulted in slight damage and wrinkles in the cups.

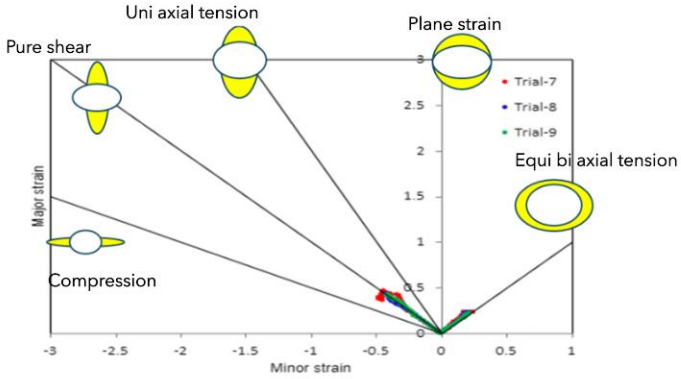

Fig 11(c). FLD of trials 7,8&9 with 1 mm thickness

This diagram is the one with solid cluster without much of variation in the strain points. Looks like the strain values are in the limit of forming and are better at than the previous FLD diagrams.

3.6 Fabrication of Deep drawn cups

The deep drawn cups are made using deep drawing machine with hydraulic powered press. The blanks are cut to the calculated diameter and is heated to the required temperature. The heated blank and is safely put above the die cavity and the hydraulic press is applied to get the cups and then it is removed and placed aside to cool down.

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Fig 12. Deep drawing machine with hydraulic powered press

The lever is used to advance the press towards blank material and die and also withdrawn when shape of the cup assumes the shape of the die completely. After the drawing is done, using the tongs the cup is removed from the die cavity.

Fig 13. Trail 8 cup

IV. CONCLUSION

The performance of sheet metal during forming processes is influenced by various factors, including temperature, thickness, coefficient of friction, and strain rate. Increased temperature leads to a decrease in the effective stress of the sheet metal, while the surface expansion ratio increases. Interestingly, damage initially decreases with increasing temperature but then starts to increase again. The thickness of the sheet metal also plays a role, with thinner materials (0.5 mm) experiencing more effective stress compared to thicker ones. The effective strain shows a notable value at 0.5 mm thickness, but not much change is observed for thicknesses of 1 mm and above. The surface expansion ratio increases with increasing thickness, and damage is inversely proportional to thickness, meaning thicker materials tend to have less damage. The coefficient of friction also affects the forming process, with the effective strain fluctuating as the coefficient changes. The surface expansion ratio is less at low coefficients of friction and remains steady at higher coefficients. Finally, the strain rate has a significant impact, with effective strain increasing and then decreasing as the strain rate increases, while damage consistently increases

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with higher strain rates. Understanding the interplay of these factors is crucial for optimizing sheet metal forming processes and ensuring the desired performance of the final product.

The optimal cup found within the process parameters with little damage is found to be the cup of trial number 8 with factors 1 mm, 300℃, 0.02 and 1000 s^{-1} .

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