Experimental and Computational Investigation of the Impact of Geometry Variation on Rollover in Sheet Metal Cutting

Ashutosh Kolhatkar, Anand Pandey

***Abstract*— Except smooth sheared edge, the other characteristic elements such as rollover, fracture, dishing or the burr are considered defects in the shearing operation. The functional quality of a blank is known by least and uniform rollover. Though several processes are developed today to reduce the rollover, these processes are with limitations from cost and tooling construction point of view. Experiments and simulation analysis were conducted to analyse the shearing process for the impact of geometry angle variation and the corner radius on the rollover. The study has revealed that the rollover increases with the reduction in the blank geometry angle and the corner radius. The paper will help understand aspects other than clearance & material properties on rollover formation.**

***Index Terms*—Rollover, Shearing action, Sheet metal**

I. INTRODUCTION

SHEET metal stamping continues to be the most preferred process for the cost benefits in high volume production. The increasing quality demands & cost pressures from the customer are the drivers in the development of tooling industry. Sheet metal cutting is the primary operation while converting sheet into the product. The characteristics of the sheared edge & the flatness determine the blank quality. For the sheared edge, except burnishing band, other inevitable characteristics like rollover, fracture, burr & dishing are considered defects. For rollover, concern has also been the nonuniform rollover in the blank. Much research over the past 6 decades has attempted to understand the effect of shearing action on rollover formation as illustrated in Section II. The process depends on several factors, every research in the field is adding value to the knowledge base about shearing action and the rollover effect. The section on methods to reduce rollover elaborates on developments in the tooling to increase the sheared edge by reducing rollover, fracture & the burr formation. While these studies tell about the characteristics of the rollover formation, the combined effect of geometry profile, corner radius, and clearance on the rollover is yet to be studied. The experimental setup to evaluate the effect of geometry on the rollover backed by validation using the simulation method has helped understand the shearing process. The results found by these experiments will be useful to enhance the know-how about the rollover formation & to find remedies in minimising the impact. The study also illustrates the critical factors to be considered in the product design for improving the tooling element life.

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II. RELATED WORK

A. Understanding Rollover Effect

The schematic (Fig. 1) shows the stage of rollover formation in the punching operation. The plastic deformation of the material causes the rollover formation.

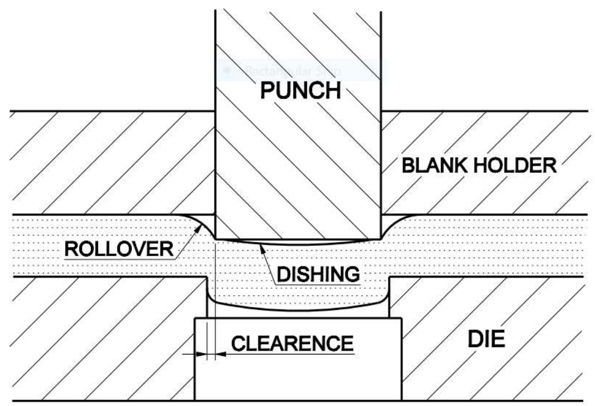

Fig. 1. Rollover formation - Schematic

Maeda and Tamura [1] termed rollover as shear droop. The experiments in hole punching in mild steel & copper showed that shearing resistance increases with an increase in the clearance and reduction in hole size. Dusil [2] termed the characteristics of material dragging within the gap of punch-and-die element as Vane. While using Visio plasticity & strain gauge, Kasuga et al. [3] analysed the metal flow during shearing process. It was observed how hydrostatic pressure impacts rollover height & overall penetration with change in clearance. While describing the characteristics of shear affected zone by analysis of experimental data of trimming and piercing process, Levy and Tyne [4] studied the effect of clearance and tensile strength on rollover percentage. Regression analysis was done (1) to quantify rollover percentage for two data sets and concluded that there are other

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shearing process variables affecting the rollover other than clearance and tensile strength.

$$\text{Rollover \%} = a_0 + [\, a_1 \text{ x clearance (\%)}] + [a_2 \text{ x } \tau_s] \qquad (1)$$

Sasada and Togashi [5] stated that rollover material flow is caused in two directions. The amount of rollover is the summation of the area of the lateral displacement and area of clearance insufficiency. When the clearance is small, lateral factors strongly affect (2) & the lateral displacement is higher in the initial phase of punch entry. In case of large clearance, material displacement in the clearance direction is found to be predominant (3).

$$A_{Lateral\ material\ flow} = \int_0^t D1(y)dy + \int_0^t D2\,(y)dy \qquad (2)$$

$$A_{Material\ insufficiency} = \text{Clearance x vert. displacement} \qquad (3)$$

B. Methods to Reduce Rollover

While phenomena of rollover are inevitable, number of attempts have been made to reduce or eliminate rollover & increase the sheared edge percentage. Fig. 2 shows various methods adopted and tried for reduction of rollover. Shaving process is two staged process of recutting the earlier sheared edge to make it smoother. Sontamino and Thipprakman [6] further studied the process in view of smaller shearing clearance and larger shaving allowance to reduce die rollover formation by simulation and experimental method. In another experiment [7], die geometries were modified by providing a rake angle to reduce rollover in shaving operation. Chung et al. [8] has also suggested progressive layout with half blanking and blank-shaving process to reduce rollover. Katoh and Kondo [9] experimented with a modified square-shaped punch having a 3D formed radius at punch corners in the axial direction to increase the rollover% in SAPH440 & SAFH590 materials of 3.5 mm thickness. Senn and Liewald [10] modified the punch to a concave nose shape. This change ensured the normal pressure transmission in conventional cutting. Simulation results have shown that the burnishing band percentage is doubled, whereas rollover and fractured zone have drastically reduced.

Senn and Liewald [11] during the investigation of edge hardening explained the double staged counter cutting method to have a clean sheared edge. Lee et al. [12] while comparing fine blanking with conventional blanking elaborated on constructional requirements of the tool with negligible cutting clearance and v-ring used on triple action hydraulic press. It was further detailed with the effect of straining or hardening of the blanking edges surrounding the sheared edge. Lee et al. [13] explained the principles and mechanism of fine blanking from tooling, cutting clearance, v-ring indenter, cutting speed, counter balancing force, press requirement and material properties viewpoint, to achieve smooth cut band. This process avoids tensile stretching of the material, thus reducing the rollover and eliminating premature fracture. Fuchiwaki et al. [14] evaluated the fine blanking process to demonstrate the dependence of shear droop on part profile shape. In the experiment, a shear droop varied from 7.1% to 32.9% for the part geometry tested. This experiment also showed that work hardening property has higher impact on the rollover than the tensile strength of the material. Aravind et al. [15] used rubber for counter force in fine blanking instead of conventional triple action to further improve smooth sheared edge percentage in EDD grade steel. Liu et al. [16] modified die design with additional v-ring in fine blanking for further reduction in the rollover.

The overall study of rollover effect & various remedies to reduce rollover has revealed that due to the clearance gap, there is variation in the rollover as the sheet metal initially tries to flow in the gap. Understanding of the tensile strength & strain hardening is essential to improve sheared edge characteristics of the metal that causes restraining force for metal flow. The blank holder pressure impacts the restriction to metal flow. Even after these studies, the variation in the rollover for a given blank geometry is uncontrollable. The paper hereafter illustrates the methodology adopted to understand the rollover formation from the part geometry perspective.

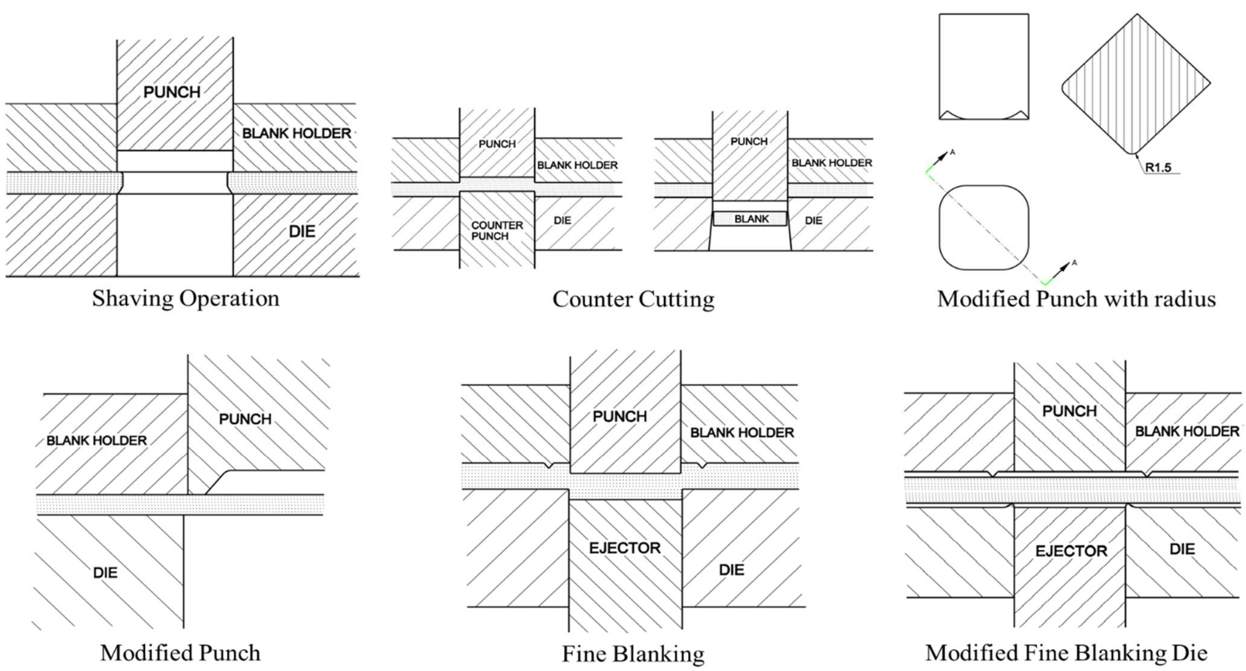

Fig. 2. Methods to reduce rollover

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III. SETUP CONDITIONS

A. Experimental Set-up

The progressive tooling was designed & manufactured with high precision. The die & punch material used was Bohler made AISI D2 hardened & tempered at 59–61 HRC for high wear resistance & through hardening properties. Spring loaded stripper & ball cage construction ensured precision aspect of the tool construction. The strip layout shown in fig. 3 ensured enough bridge is provided to avoid dragging effect in nearby cutting operations. The three geometrical profiles allowed the parameters measurement from 60° to 120°, corner radius ranging from 0.2 mm to 3 mm. Replaceable die insert & punch construction reduced the size of tooling & the cost.

Table I Material Properties

Chemical Properties				Mechanical Properties			
C %	Mn %	S %	Ph %	Tensile Strength	Yield Stress MPa (Max)	Elongation %	Hardness HRB
0.12	0.5	0.04	0.04	300	280	28	65

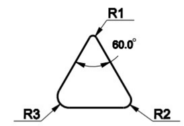
Table II Clearance Range

Material Thickness	0.8 mm	1.0 mm	1.2 mm	1.5 mm
Clearance	7.5%	6%	5%	4%

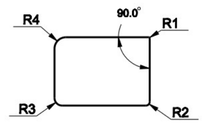
Fig. 4 shows the blanking profiles with the table enlisting the corner radius given to the die insert. Table I shows the properties of Cold Rolled Cold Annealed Steel material used for the experiment.

Experiments were conducted with four material thickness ranging from 0.8 mm to 1.5 mm in the same die; getting variation in cutting clearance percentage. This combination enabled the rollover analysis along with the clearance percentage. Table II shows the thickness & the clearance percentage used in the die.

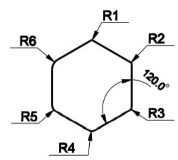
The geometries of the blanks were selected such that the effect of angle from 60° to 120° can be evaluated in relation to the corner radius. So overall combination of corner radius from 0.2 R to 3 R, angle from 60° to 120°, material thickness from 0.8 to 1.6 mm & clearance 3.75% to 7.5% are achieved in the experiment for analysis. Rollover measurement was done on the blanks using 67 times zoom vision measurement system.



R1	R2	R3
0.2	0.4	0.6
0.8	1.0	1.2
1.5	1.7	2.0
2.2	2.5	3.0



R1	R2	R3	R4
0.2	0.4	0.6	0.8
1.0	1.2	1.5	1.7
2.0	2.2	2.5	3.0



R1	R2	R3	R4	R5	R6
0.2	0.4	0.6	0.8	1.0	1.2
1.5	1.7	2.0	2.2	2.5	3.0

Fig. 4. Component geometry Dimensions

B. Numerical Simulation

Ansys 16.0 Numerical software was used for the analysis. The geometrical models used for testing conditions conformed to the experimental setup. The Punch, die & the sheet metal were considered elastoplastic. The material used for Punch and die were Steel S-7 and that for sheet, Steel 1006 (Table III). For explicit dynamic simulation, Johnson Cook (JC) damage model [17] is considered. The JC model is considered most suitable for the conditions of high strain rate, large strain & conditions of elevated temperature. It is a purely empirical model (4), which evaluates equivalent plastic strain (σ_{eq}).

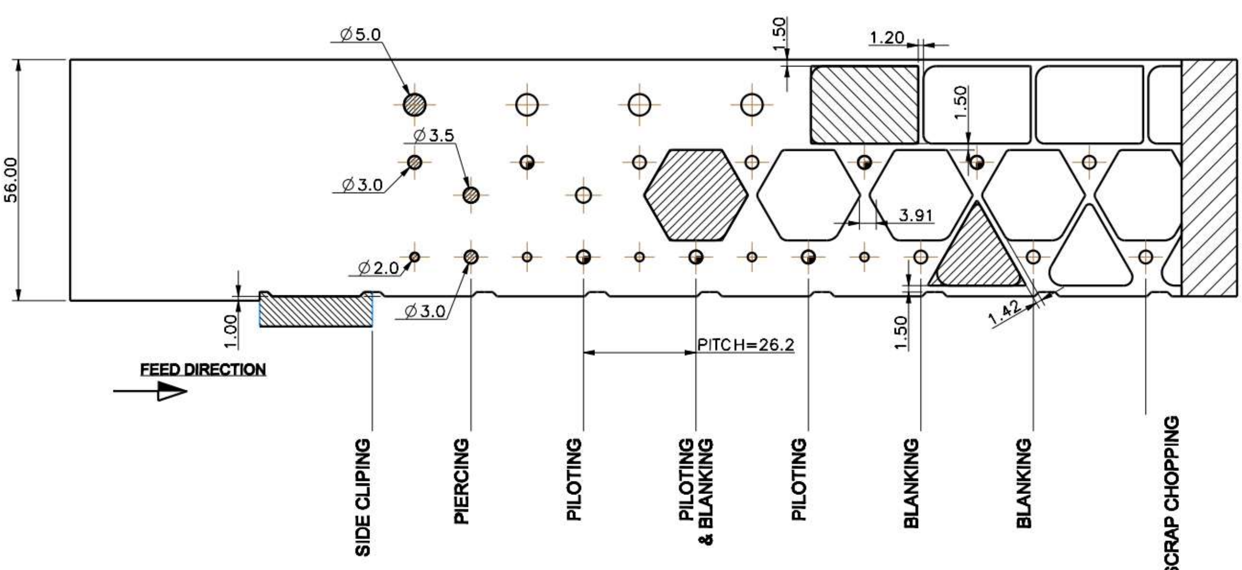


Fig. 3. Strip layout

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σ_{eq} = [A + B$(\varepsilon_p)^n$] [1 + C $\ln(\acute{\varepsilon}_p{}^*)$] [1 – ((T − T_0)/ (T_m − T_0)^m)] (4)

Where

A - Yield stress (MPa)	ε_p – Accumulated plastic strain
B – Strain hardening parameter	$\acute{\varepsilon}_p{}^*$ - Dimensionless strain rate
n – Strain hardening exponent	T – Working temperature
C – Strain rate sensitivity parameter	T_0 – Room temperature
m – Temperature exponent	T_m – Melt temperature

The JC model is built-in to consider power law; the strain rate effect and the temperature effect. The first term [A+B$(\varepsilon_p)^n$] specifies the hardening law. The second term [1+C ln$(\acute{\varepsilon}_p{}^*)$] considers the strain rate, whereas the last term [1–((T − T_0)/ ($T_m - T_0$)^m)] considers the temperature effect. For the simulation, temperature exponent is taken as one thus nullifying the effect of temperature.

Simulation is conducted for extreme conditions of geometry, radius & clearance to validate the effect on rollover. To save computational time, only the part of the whole system was considered. The frictional contact between the punch and sheet was modelled using Coulomb's law with the friction factor set to 0.1. The punch speed was set to 100 mm/s, but the effects of temperature were neglected. To solve this problem, smaller elements were arranged around the cutting edges and an adaptive remeshing strategy was used. Maximum principal strain was considered as 0.4, whereas Maximum shear strain was considered as 0.8 under principal strain failure. Maximum stress conditions were recorded at the corner condition.

Table III Mechanical properties of sheet steel & tool steel used for simulation used from Ansys material library

Material/Properties	Steel 1006	Tool Steel S-7
Hardness	F-94	C-50
Density	7890	7750
Yield Stress (MPa)	350	1539
Strain Hardening Parameter (MPa)	275	477
Strain Hardening exponent	0.36	0.18
Strain rate sensitivity Parameter	0.022	0.012
Temperature Exponent	1.0	1.0

IV. RESULTS AND DISCUSSION

A. Effect of Blanking Profile on Rollover

The relationship between rollover%, clearance% & radius is shown in fig. 5 to 7. This relationship is shown separately for the clearances and angle values under consideration in the experiment. It is evident from the graph that rollover is not only dependent on clearance as stated by various researchers, but it is also dependent on the corner angle & the included angle. The graphs show a typical pattern to follow. For 120° the effect of radius is marginal, whereas as the angle reduces, the effect is seen significantly. This trend is seen in the graphs of 60° blanks, where rollover percentage increases significantly as the radius reduces. Data show that the clearance and rollover% are directly proportional to each other, whereas the rollover% is inversely proportional to the angle and radius.

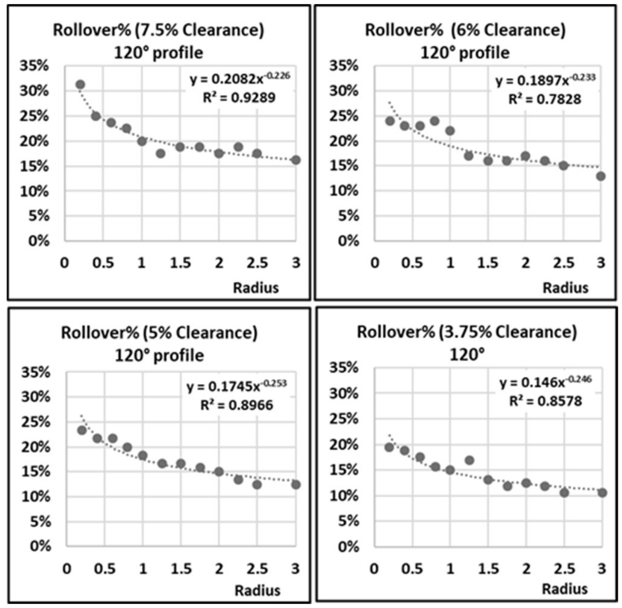

Fig. 5. Rollover measurement for 120° profile

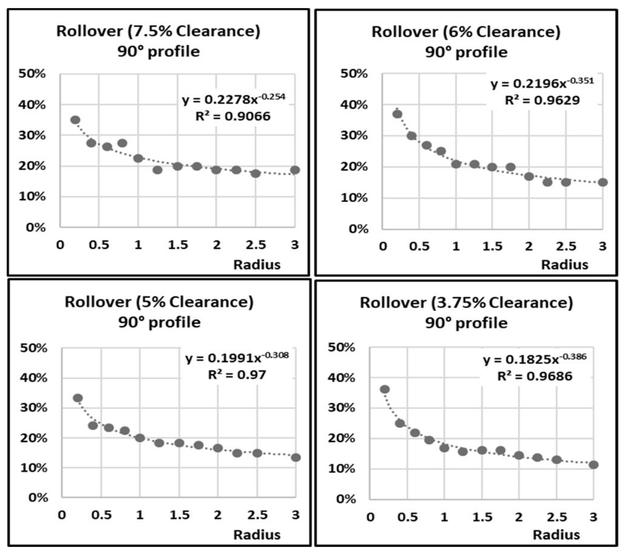

Fig. 6. Rollover measurement for 90° profile

Also, the pattern formed by the data is nonlinear. The nonlinear regression analysis shows a peculiar power function with the data. The best fit analysis for the data with combined data of points with all clearances is considered to test the pattern. Based on the data, a constant value in the equation is rounded off. Also, the power value for a set of data of common angle blanks is rounded off to test the proportion of variance for the entire set of data.

For 120° data, the rollover against radius follows an equation, Rollover% = $\frac{0.2}{\sqrt[4]{Radius}}$. For the total data set proportion of variance R^2 was 0.608. This trend is seen in fig. 8. So compared with separate clearance dataset, R^2 value is low when the entire dataset is considered. This comparison

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shows that for 120° angle, the impact of clearance is vital. For angles larger than 120° till the straight edge, clearance% has a major contribution on rollover%. Graph also shows that for a radius of less than 0.5 mm in 120° blanks, radius factor needs to be considered along with the effect of clearance.

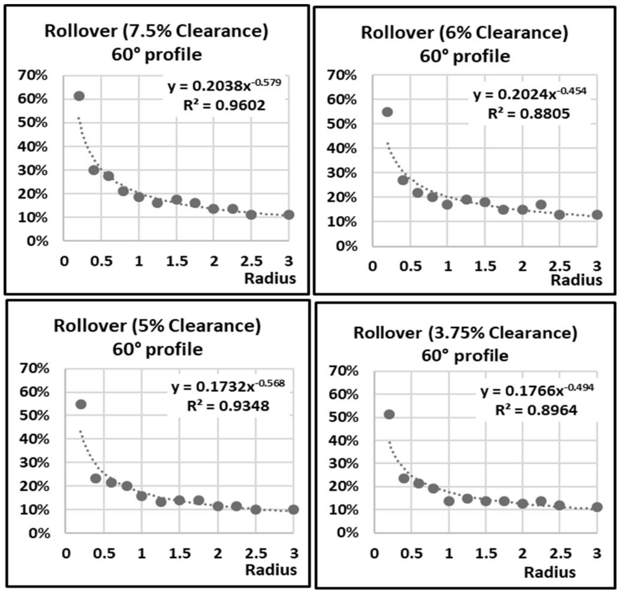

Fig. 7. Rollover measurement for 60° profile

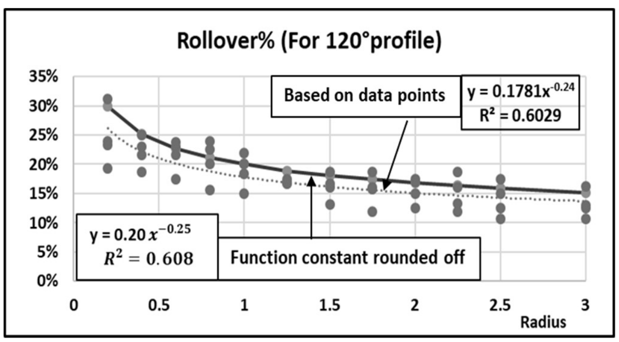

Fig. 8. Regression of 120° profile rollover data

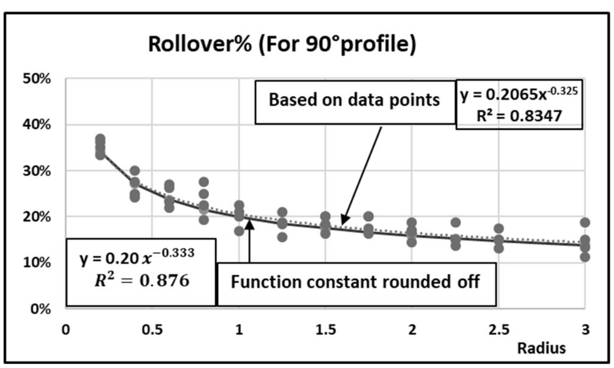

Fig. 9. Regression of 90° profile rollover data

The angle 90° has the maximum application in blanking profiles. For 90° data, the rollover against radius follows an equation, Rollover% = $\frac{0.2}{\sqrt[3]{Radius}}$. For the total data set proportion of variance R^2 was 0.88. Fig. 9 shows that there is a strong relationship with radius for blanks with 90°.

For 60° data (Fig. 10), the rollover against radius follows an equation, Rollover% = $\frac{0.2}{\sqrt[2]{Radius}}$. For the total data set proportion of variance R^2 was 0.88. As the radius reduces, significant rise in rollover% is seen. This effect is prominently seen when the radius is below 1.0 mm. The situation of extreme condition of low radius & acute angles is showing the highest rollover%.

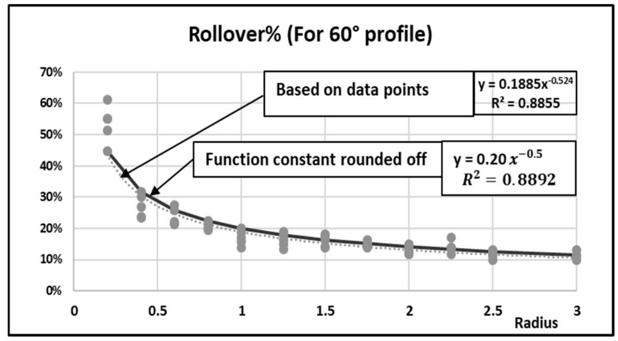

Fig. 10. Regression of 60° profile rollover data

To understand this extreme situation better, combined effect of angles, radii on rollover% is studied. The normalised data surface plot (fig. 11) depicts that there is a concentrated effect at the corner. With the reduction in the corner angle as well as the corner radius, there is a stressful situation on the blank. This causes dragging of the material that results in a higher percentage of rollover. The data can be distributed in 3 phases. The lighter phase is the phase where radius does not have much impact on rollover%. The little darker zone is low critical zone where the rollover% is from 20% to 40% and the stress condition on tooling element is manageable. The most critical zone is the darkest zone with rollover% more than 40%, which typically has higher strain conditions and major impact on life of tooling elements like punch & die.

Radius	60°	90°	120°
0.2	44.7%	34.2%	29.9%
0.4	31.6%	27.1%	25.1%
0.6	25.8%	23.7%	22.7%
0.8	22.4%	21.5%	21.1%
1	20.0%	20.0%	20.0%
1.25	17.9%	18.6%	18.9%
1.5	16.3%	17.5%	18.1%
1.75	15.1%	16.6%	17.4%
2	14.1%	15.9%	16.8%
2.25	13.3%	15.3%	16.3%
2.5	12.6%	14.7%	15.9%
3	11.5%	13.9%	15.2%

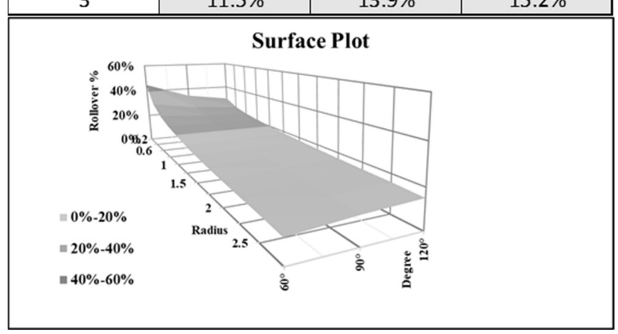

Fig. 11. Data set and surface plot of the combined effect on rollover

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B. *Rollover Generation at 60° Profile*

Based on the regression analysis, it was evident that there is a larger impact of 60° profile & reduced radius on rollover.

To validate the result & to test the hypothesis, more data were collected, especially for 60° profile samples. It was important to analyse the stresses on tooling elements in case of such extreme conditions. Numerical analysis has shown a distinct variation in the rollover formation for 60° angle profile when compared with more than 90° angle profile.

Stresses on punch for 4 extreme conditions were studied. The least stress was observed at 120° profile with 3 mm radius, whereas the highest stress condition was at 60° angle and 0.2 mm radius. The extreme stress condition of the punch will impact the punch life.

The continuous use of the tool causes rounding of the punch edge quickly or may even turn to chip-off or the breakage of the punch. It is important to avoid such situations from the product design perspective. The darkest zone, as shown in the surface plot is critical zone in that regard and becomes the limiting value in product design.

V. CONCLUSION

The paper illustrates the effect of blank profile on rollover using experiment & numerical simulation. The rollover depth was compared for various angular profiles ranging from 60° to 120° & radius ranging from 0.2 mm to 3.0 mm along with changes in clearance %.

Rollover increases with a reduction in angle. The increase is very sharp for acute 60° profile. Numerical simulation revealed a similar pattern formation for the change in profile degree condition.

Rollover increases with a reduction in radius. Rollover increases sharply when the radius reduces below 0.4 mm for angles below 90°.

The stresses on the cutting element increase significantly for a combination of acute angles below 90° and a radius below 0.4. This combined situation needs to be avoided in product design to enhance basic life of cutting elements.

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