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Numerical investigation of key stamping process parameters influencing tool life and wear

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Abstract

The influence of various combinations of punch and die materials, such as different carbide grades, and also the cutting radius on tool wear is the aim of this investigation. The numerical analysis results are supported by the relevant experimental evidence to validate the main model assumptions such as assumed material flow stress curve and the damage criteria. Taguchi method is utilised to effectively model and analyse relationship between process parameters. Roll-over and burr formation for a given punch-die clearance and cutting radius have been discussed and analysed in terms of tool wear reduction for different materials.

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Keywords: Wear; Metal stamping; Wear modelling; Finite element model; Taguchi method; Orthogonal pairing

1. Introduction

Sheet metal stamping processes are one of the widely used manufacturing process for producing large volume high quality parts [1]. In the sheet metal stamping process, the metallic sheet is placed between the punch and die, and the required cutting action is performed by the downward movement of the punch. The produced part edge is characterized by four zones namely roll-over, shear, fracture and burr [2]. Tool wear is a dynamic process, which is affected by geometry of punch and die, material properties and other process factors [3]. Tool wear contributes to a substantial

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cost towards manufacturing of the tools. In addition, excessive tool wear leads to substantial tool downtimes. The estimation of tool wear is important for scheduling tool changes and for process control and optimization. Literature shows that numerous studies have been undertaken to understand tool wear. Maeda and Matsuno [4] have investigated how wear increased on cutting edges with the increased number of parts blanked. The authors also investigated the influence of wear on blanking force, energy, dimensional accuracy and burr height. Hoffmann et al. [5] have proposed an advanced simulation approach using geometry-update-scheme to consider geometry changes in tool wear. Cheung et al. [6] have examined experimentally the tool wear in dam-bar cutting for integrated circuit packages. The results indicate that punch flank wear increases with increase in punch-die clearance. High speed steel showed poor performance to wear comparing to tungsten carbide. R Hambli et al. [7] have utilized finite element method to model blanking process and also considered the influence of tool wear on burr height evolution. The proposed model was used for predicting tool regrinding by comparing the burr height. A wear algorithm has been developed by Falconnet et al. [1] using experimental wear data and mechanical fields computed from blanking simulation process. Die wear has been studied by defining three stage co-efficient K for advanced high strength steel sheet metal forming process [3]. The authors utilized die wear severity index calculated as an integral of stress and slide speed over time duration. Die wear was calculated as the product of wear severity index and wear co-efficient.

In previous studies, variations of part characteristics, such as burr and roll-over, are considered as a total influence of both punch and die. In this study, punch wear and die wear is studied individually and their impact on the part characteristics is investigated in detail. Additionally, the influence of the different punch and die materials on the tool wear has been examined and discussed.

2. FE based numerical model: fracture and adhesive wear aspects

Blanking process leads to very high deformations of a metal workpiece resulted in its fracturing and complete removal from the primary metal strip or sheet when it is punched. The workpiece is punched into a die during the process shearing the part out. The model of the process considered in this work is FE based, axisymmetric and quasi-static. The model setup is shown in Fig. 1(a). The punch diameter is 5 mm and the workpiece has a thickness of 0.38 mm. The sheet is modelled as elastic-plastic material, while both the punch and die are simulated as elastic materials and the stripper has been assumed as a rigid body. The punch is assumed to be moving in the vertical downward direction at a certain velocity while maintaining the die bottom edge in the fixed position. The stripper force is applied in negative y direction. The frictional interaction is simulated accepting Coulomb friction law with the coefficient of friction assumed to be of 0.3 between the punch and the sheet and of 0.2 between other contact surfaces in the modelled system.

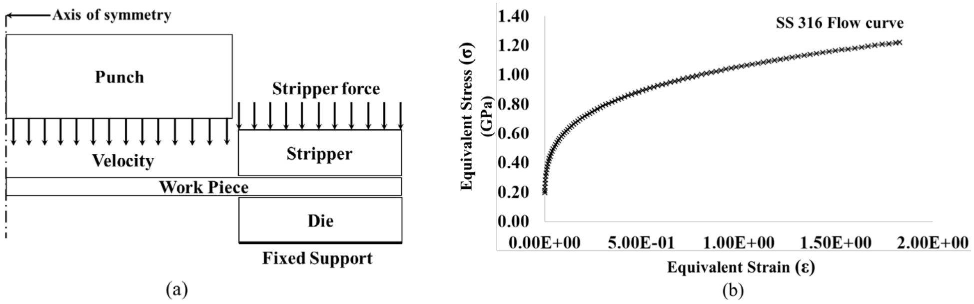


Fig. 1. (a) FEM model setup of simulated model and (b) flow curve of SS 316 model.

The tool life and tool wear in the blanking process was studied using workpiece made of austenitic 316 stainless steel. The steel is assumed to be an isotropic material with the density of 7.9e-6 Kg/mm^3, Young Modulus of 193 GPa and Poisson's ration of 0.33 following Von-Mises yield criterion. The multilinear representation of the material's true stress-strain curve has been implemented into the model based on the available data as shown in Fig. 1 (b). 2D mesher capability of LS dyna is utilized to mesh the model, 100 and 50 number of elements per edge mesh size used on punch and die respectively. Fine mesh sizes were used to model the cutting edge to accommodate tool wear profile.

The shear failure criteria has been utilized to model the blanking process. The shear failure model utilizes accumulated effective plastic failure strain to model fracture [8] as defined in equations (1) and (2). According to the accepted model, the failure occurs when the effective plastic strain reaches effective plastic failure strain which is a user defined parameter.

$$\varepsilon_{eff}^{p} = \int_0^t d\,\varepsilon_{eff}^{p}, \tag{1}$$

where the effective strain $d\varepsilon_{eff}^{p} = \sqrt{\frac{2}{3} d\varepsilon_{ij}^{p} d\varepsilon_{ij}^{p}}$. (2)

It was assumed that fracture occurs by element deletion when the critical value of the effective strain is reached. The similar shear failure model has been utilized by Frazin et al. [9] for simulation of blanking process. Similarly, Ghosh et al. [10] have established that the fracture initiation and crack propagation are in good correlation with experiment, as predicted by shear model. Falconnet et al. [1] have utilized shear model to understand punch wear in blanking of copper alloy sheets.

In order to verify the model assumptions, a hole of 5 mm in diameter on a 0.38 mm thick 316 stainless steel with 5 % a side punch and die cutting clearance has been stamped as shown in Fig. 2 (a).

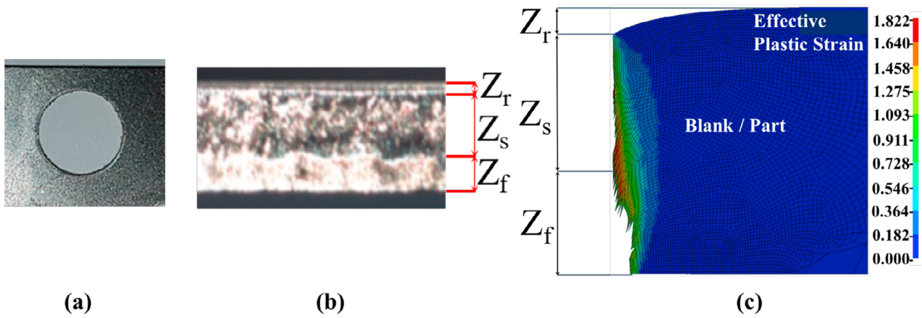


Fig. 2. (a) Top view of workpiece, blanked edge characteristics using (b) experiment and (c) simulation.

The following edge parameters on the strip such as roll-over zone (Zr), shear zone (Zs) and the fracture zone (Zf) obtained during the simulation were in good agreement with the corresponding experimental results (Table 1) and Fig. 2(b) and (c).

Table 1. Comparison of experimental and simulated blanked edge parameters for blanking 5 mm hole in 0.38 mm thick 316 stainless steel.

Method	Edge Characteristics (in mm)		
	Roll-Over (zr)	Shear (zs)	Fracture (zf)
Experiment	0.0412	0.200	0.148
Simulation	0.0398	0.211	0.129

In the metal stamping process, the relative motion between the two contact surfaces such as sheet and punch or die causes the loss of tool material through adhesive wear [1, 7]. The wear process is instigated by the interfacial junctions that are formed at the contact zones [11]. Based on Archard's law, which is widely used for numerical modelling of tool wear [3, 12], adhesive wear volume is directly proportional to the applied normal load, sliding distance and inversely proportional to the hardness of the softer material.

$$W = \frac{k.F_n.s}{H}, \tag{3}$$

where W is the adhesive wear volume, k is the wear co-efficient, Fn is the applied normal load, s is the sliding distance and H is the hardness of softer material. The typical values of k for a wide variety of combination of contacting materials depending on the sliding contact conditions are presented in literature [7, 11]. In this work, the wear volume is calculated using Archard's wear equation for each element across the cutting edges of both the tool and the die to accommodate face and side wear, as shown in Fig. 3(a).

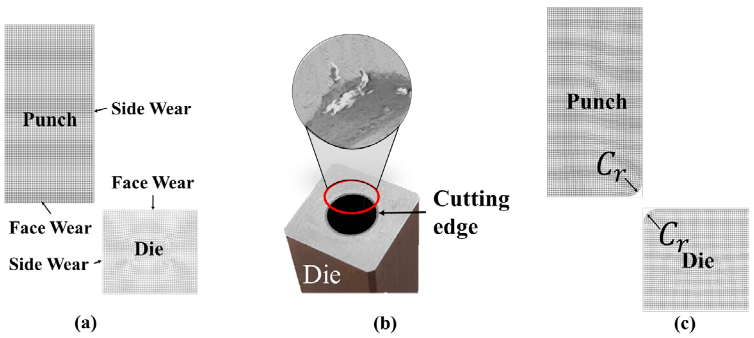


Fig. 3. (a) Wear profile for punch and die (b) Experimental die wear profile (c) Representation of worn edge in model.

3. Results and discussion

Set A - Design of numerical trials: The tooling design and blank development is a complex process, which involves choice of various process parameters such as sheet, punch and die materials, cutting clearances, etc. [7, 13]. Understanding the relationship between these parameters and tool wear is important and crucial for making an appropriate tool life prediction. Capturing these relationships and quantifying them will lead to minimizing the overall production cost [8]. It can be seen that wear causes the cutting edge of the tool to be rounded off (Fig. 3(b)). The wear is accounted for by modelling cutting edge radii for both punch and die (Fig. 3(c)). Similar observations regarding modelling of tool wear have been made by other authors [1, 7]. The process parameters and their corresponding levels chosen for Set A of the numerical trials are presented in Table 2.

Table 2. Process parameters and its levels: Set A.

Process parameter	Levels
Punch Material	CPM 10V (S); CF – H40S+ (M); CF-20HP (H)
Die Material	CPM 10V (S); CF – H40S+ (M); CF-20HP (H)
Clearance (per side, %)	3; 5; 7.5; 10
Velocity (%)	100; 125; 75; 50
Cutting Edge Radii (Cr) (mm)	0; 0.01; 0.02; 0.03

The levels in Table 2 represent the different parameter values. CPM® 10V (Hardness: 773 HV) is standard tool steel material by ZAPP® while CF-H40S+ (Hardness: 1400 HV) is a corrosion resistant medium/fine grade carbide and CF-20HP (Hardness: 1300 HV) is corrosion resistant/submicron grade carbide from Ceratizit®. In the current study, CPM® 10V is considered soft (S), while CF-H40S+ carbide is considered medium (M) and CF-20HP carbide is assumed as hard grade based on its stiffness. The model has been developed to simulate the production run and the velocity in Table 2 is varied accordingly as percentage of the production velocity taken as a base. Capturing all the variations in these parameters would require performing 1296 modelling trials. Hence, Taguchi's method or orthogonal pairing is utilized to reduce the trails allowing for maintaining the effects of each variable on to the final output [14]. As shown in Table 2, there are 5 process parameters with maximum 4 and minimum 3 levels. To optimize the design of experiments, maximum number of levels is considered. For a combination of 5 parameters and 4 levels L16 orthogonal array is selected [15]. Alternatively, the minimum number of experiments that needs to be performed is determined based on the following equation [14]:

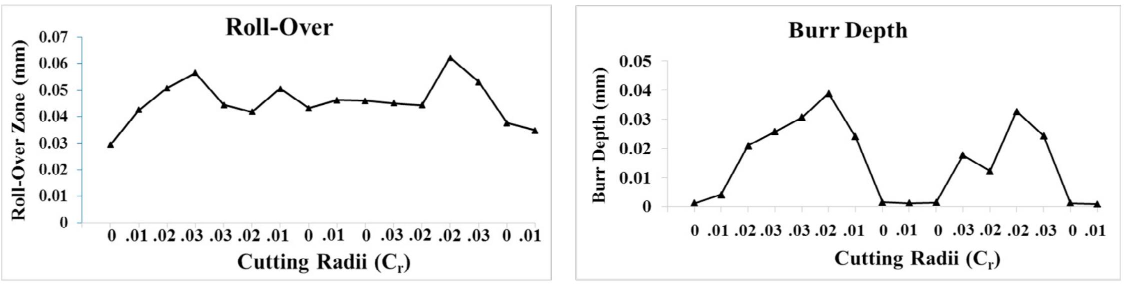
$$N = 1 + (L-1)\,P_d\,, \tag{4}$$

where N is the number of experiments, L represents the level and Pd is the process parameters. Thus, the minimum number of the trials for understanding the peak and mean wear volume along the cutting edge for punch and die and their influence on part characteristics can be reduced to 16 (Table 3).

Table 3. L16 orthogonal array used for experimental design.

Trial No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Punch	S	S	S	S	M	M	M	M	H	H	H	H	M	S	H	M
Die	S	M	H	M	S	M	H	S	S	M	H	M	S	M	H	S
Clearance	3	5	7.5	10	5	3	10	7.5	7.5	10	3	5	10	7.5	5	3
Velocity	100	125	75	50	75	50	100	125	50	75	125	100	125	100	50	75
Radii (Cr)	0	.01	.02	.03	.03	.02	.01	0	.01	0	.03	.02	.02	.03	0	.01

Set A – Results: Fig. 4(a) illustrates variation of the roll-over against cutting radii and clearance presented in Table 3 for the set of trails, showing a tendency to increase with cutting radii and cutting clearance.



(a) (b)

Fig. 4. Variation of roll-over and burr depth for set A experiments.

However, comparing the results of similar clearance but different cutting radii, for example trial 2 and trial 12, the value of roll-over is higher for trial 12, which has a larger cutting radius compared to trial 2 indicating the tendency of high roll-over formation for a larger cutting radius for a given clearance.

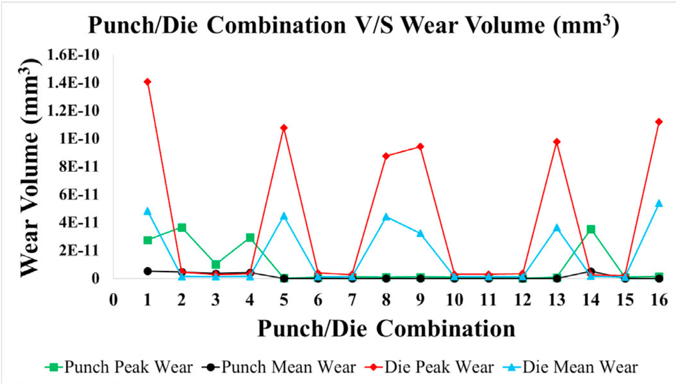


Fig. 5. Mean and peak wear volume (mm^3) for each punch/die combination.

Fig. 4(b) shows variation of the burr depth against cutting radii and clearance described in Table 3 for the different trials. The burr depth increases with increase in the die cutting radii showing indifferent behavior for varying cutting clearances. For example, trial 3 has maximum burr depth value for 3% clearance and cutting radii of 0.02 comparing to trial 12, which has the same cutting radii but larger cutting clearance. This can be related to ductility and hardness of the material being stamped and its ability to flow during stamping. Fig. 5 illustrates the wear characteristics for each punch/die combination. It can be noticed that the two grades of carbide out performed CPM® 10-V in terms of peak and mean punch and die wear.

Set B - Design of numerical trials: Based on the results of Set-A, the roll-over showed a tendency to increase with the increase of the punch cutting radii. The burr formation also increased with the die cutting radii. However, larger clearance reduced the burr for the similar cutting edge. To clarify the noticed phenomenon, a new set of numerical trials has been designed (Table 4). In Set-B, all the trials are performed for the single 3% clearance. Based on the results obtained from Set-A, CPM® 10-V was eliminated exhibiting poor wear resistance comparing to carbides. The single cutting radii of 0.02 mm is considered and the cutting radii on punch and die are treated separately.

Table 4. Set-B experimental design.

Exp No	1	2	3	4	5	6	7
Punch	M	M	H	H	M	M	H
Die	M	H	M	H	M	H	H
Punch radii	0	0.02	0.02	0	0	0.02	0
Die radii	0	0.02	0	0.02	0.02	0	0

Set B – Results: The roll-over increases with the introduction of punch cutting radii for a given clearance (Fig 6(a)). Moreover, the cutting radii on the die has a very little influence in formation of the roll-over, as shown in trial 4 and 5, where the roll-over is at its minimum. This provides an indication that roll-over increases with the increases in punch wear. Fig 6(d) presents the variation of burr for Set-B. The burr formation increases with the presence of die radii for a given clearance. Conversely to roll-over formation, the punch cutting radii has very little impact on the formation of burr as seen in trials 3 and 6, with the maximum burr values for trails 4 and 5 suggesting that the burr formation increases with the increase in die wear. It can be seen in Fig 6(d) that the burr value for trial 5 is smaller than for trial 4. In this case, when punch and die are made of medium strength materials, as shown in trial 5, it leads to smaller burr formation comparing to trial 4, where hard materials are used. Normally, the part characteristics tend to deteriorate in metal stamping process. Hence, comparing the roll-over and burr for worn and first-off punch parts, it is possible to determine whether the punch or the die has worn for a given process.

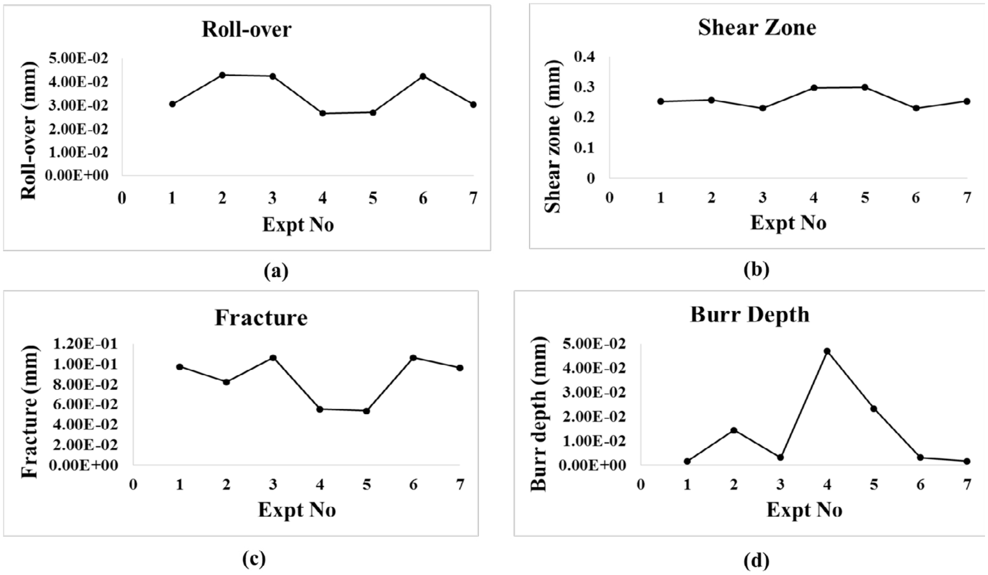


Fig. 6. Variation of part characteristics for Set-B.

This helps in scheduling the tool changes and tool maintenance [7]. Further, this also helps to redesign the punch or the die depending on the wear performance to improve its tool life. It can be seen in Fig. 6(b), that the shear zone is higher for sharp punch and reduces when the punch has a cutting radius. Conversely, fracture zone is lower for a sharp punch comparing to worn punch (Fig. 6(c)). This is because the sharp punch can penetrate further along the thickness of the metal compared to a worn punch increasing the shear and reducing fracture. Shear is at its maximum and the fracture is at minimum when the punch is sharp, and the die has a cutting radius.

Fig. 7(a) and (b) shows the variation in punch peak and mean wear volume for different tool configurations. It can be seen that peak punch wear and mean punch wear is minimum for trial 6 when the punch has a cutting edge radius and the die is sharp and both of them are made of different grade of carbide materials. The punch peak and mean wear is maximum for trial 7, where the both punch and die are made of hard grade carbide materials and have no cutting edge radii. This might because most of the tool materials are developed to withstand wear, which is caused by the normal force. When the cutting clearance is very small, the effect of impact force becomes more prominent as the parts are very close to be in line with one another hence causing more damage to the tools. The excessive damage can be avoided by either using larger clearance or making punch and die both of different grades of materials as this would make one material more sacrificial comparing to the other hence reducing the effect of impact force. In addition, the use of fine grade carbide for both punch and die provide better wear resistance when compared to sub-micron grade carbide.

Fig. 7(c) and (d) represent the variation of die peak and mean wear volume. The maximum wear on the die is found when the punch has a cutting edge radii and the die is sharp, while minimum wear is noticed when the punch is sharp and the die has cutting edge radii. In a stamping process, the cutting of the sheet is performed both by the punch and die. The punch wear results suggest that to reduce the punch wear, most of the cutting needs to be performed by the die, in the sense that punch should have a cutting radius while the die should be as sharp as possible. In contrary, to reduce the die wear punch should perform larger percentage of cutting comparing to the die. However, the application of cutting radius should be performed cautiously depending on part characteristics required. This is because punch wear causes larger roll-over formation and die wear causes larger burr formation, as can be seen in Fig 6.

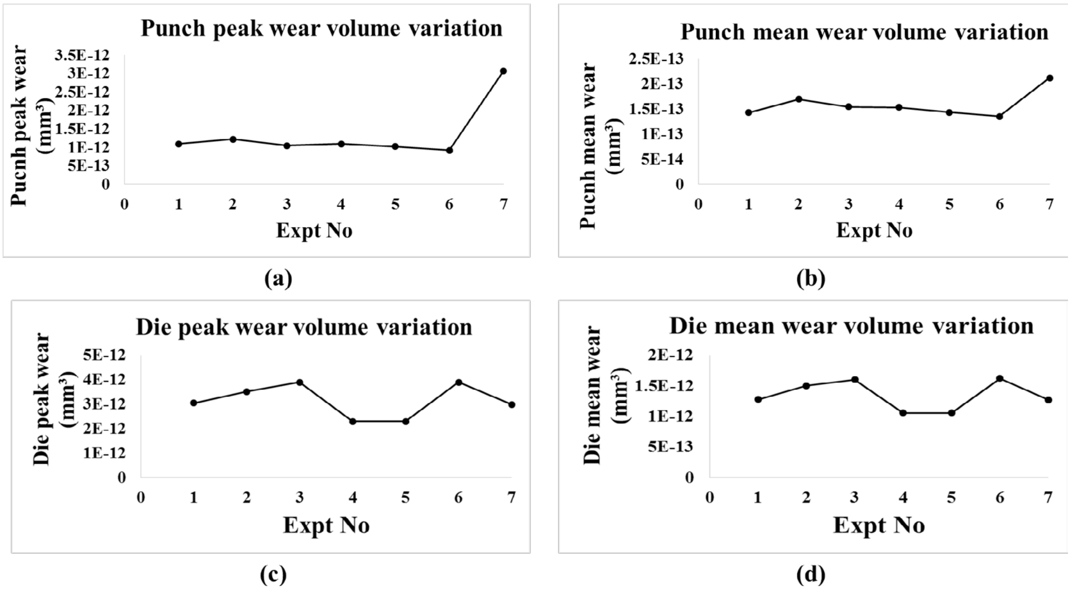


Fig. 7. Variation of punch and die peak and mean wear volume (mm^3).

4. Conclusions

The finite element model of the stamping process has been developed in this work to investigate key stamping process parameters influencing tool life and reducing tool wear. The model allows for analysis of tool wear and its influence on part characteristics. The shear failure model was assumed for fracture simulations. The obtained experimental and numerical results are in good agreement demonstrating the model's ability to predict the effects of different process parameters on tool life. The Taguchi's trial design methodology has been applied for reduction of the required numerical trials providing better understanding of process parameters influence on part characteristics and tool wear. The preliminary results showed that roll-over is influenced by punch wear while burr formation is influenced by die wear. CPM® 10-V showed very poor performance in comparison to carbide. Since the initial set of numerical trials involved too many process parameters variants, the second set of trials was performed. The obtained results demonstrated that roll-over increases with the introduction of punch wear for a given clearance and has very little influence on the formation of burr. Similarly, the burr formation increases with the introduction of die wear. Based on this observation and comparing the worn tool part characteristics with first – off parts, the wear on either the punch or the die could be identified. The shear of the part increased with higher penetration for a sharp punch while the fracture zone was correspondingly reduced. Additionally, to reduce the punch wear, a significant part of the cutting in the stamping process needs to be performed by the die. Conversely, to reduce die wear, the punch needs to perform maximum cutting operation. It is possible to achieve with introduction of radii on the cutting edge. However, the use of radii and its value should be selected based on the part characteristics required. The use of different grades of carbide materials for both punch and die show better resistance to wear compared to similar materials. The current work discusses the influence of tool wear on part characteristics, however it does not consider dynamic wear formulation. The relevant dynamic adaption of the tool geometry based on its wear allowing for understanding of the part deterioration is going to be considered in our further work.

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