An Investigation on Tool Wear Prediction in Automotive Sheet Metal Stamping Die Using Numerical Simulation

X. Z. Wang, S. H. Masood, and M. E. Dingle

Abstract—**Prediction of tool wear in rapid production of sheet metal stamping in automobile industries is a highly challenging task as there are many control parameters involved in the production of automotive panels. This paper presents a numerical simulation methodology to investigate the effects of various processing parameters, such as the lubrication, binder pressure and surface coating, on the critical tool worn area of a certain sheet metal stamping die used in automotive production. The simulation was performed using the finite element software AutoForm™. Various contact pressure distributions and tool wear predictions at the critical tool worn section of the die-workpiece interface, using different processing parameters, were obtained in the simulation, which provide informative guidelines for the on-site production.**

Index Terms—**Contact pressure, finite element analysis, sheet metal stamping, tool wear prediction.**

I. INTRODUCTION

A rapidly changing automobile market demands high precision, perfect quality and a short lead time in sheet metal stamping of automobile parts. In the introduction of new series of advanced high strength steel (AHSS) and complicated three-dimensional shapes in workpieces, tool wear of sheet metal stamping dies is a major obstacle for industries to meet these demands as it causes increased die maintenance cost and scrap rate. Prediction of tool wear is a highly difficult task in sheet metal stamping of certain workpieces due to many control parameters involved, such as lubrication, binder pressure and surface coating, influencing the highest contact pressure at the die-workpiece interface.

In sheet metal working, tool wear is a progressive damage to a die surface caused by relative motion with respect to a blank surface [1]. However, due to the complicated geometric, material and nonlinear contact characteristics in the deformation of automotive parts, it is very time-consuming and costly to predict the tool worn location as well as relationships between tool wear distribution and processing control parameters by means of try-out techniques based on conventional trial and error and engineers' experiences. To overcome the limitations of the traditional method, several experimental and simulation studies have been made to study the tool worn areas under certain processing conditions in sheet metal working. Hambli *et al.* [2] have carried out a comprehensive study of numerical simulation of sheet metal cutting process by considering material shearing mechanism by finite element modelling and experimental verification. Hoffmann and Nurnberg [3] have described a novel approach to determine the wear coefficient for tool wear prediction in sheet metal forming based on cylindrical cup drawing experiments for wear measurements. Hoffmann *et al.* [4] have proposed an advanced wear simulation scheme to consider the geometry changes caused by tool wear in sheet metal forming, which can be used for optimal design of the tool geometry. Moura *et al.* [5] have carried out finite element simulation of sheet metal forming of an automotive shock absorber end-cap using DEFORM software and eliminated the wear and fracture problem by changing the punch geometry. De Saracibar and Chiumenti [6] have presented a numerical model for the simulation of friction wear behaviour in a non-linear kinematic setting and showed its applicability to provide tool wear prediction in forming process. Sandberg *et al.* [7] have studied the characterisation of tool wear in sheet metal stamping of extra high strength and ultra high strength steels by experimental investigation considering the effect of tool steel grade, surface roughness and surface treatment on galling resistance of cold forming process. Hernandez *et al.* [8] have presented an improved procedure of stamping tool die design based on numerical simulation and knowledge systematization. Hao *et al.* [9] have developed a technique for friction measurement tool-workpiece interface in sheet metal forming which can be used for process design and analysis and numerical process simulation.

A review of published literature reveals that very few studies have been made on the application of simulation software in prediction of tool wear in automotive application. Especially the effect of major process parameters such as binder pressure, lubrication and surface coating on tool wear has not received much attention. This paper presents a methodology based on the numerical simulation to predict the tool worn location, using simulation software,

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AutoForm™, and investigates the influences of various processing parameters upon critical tool worn locations using a case study of an automotive sheet metal part.

II. FINITE ELEMENT SIMULATION USING AUTOFORM™

A. *Tool wear model and AutoForm™ software*

Tool wear is usually observed as a loss of tool material through adhesive wear by a number of junctions formed in the contact area in the sheet metal forming [10]. The load applied on the die surface results in extremely high contact pressure in the contact area. As the tool surface adheres with the blank surface, the sliding friction between these two surfaces generates tiny wear particles. These high hardness particles then form the abrasive wear.

In this study, AutoForm™ software version 4.1 developed by AutoForm™ Engineering GmbH was employed to perform simulation of sheet metal forming and tool wear prediction. The software provides accurate simulations for sheet metal forming based on the static implicit approach, which can be expressed as

$$\int_{\mathrm{V}} T_{ij}\delta u_{i,j}dV = \int_{\mathrm{A}} t_i \delta u_i dA \tag{1}$$

where V is the volume, A is the surface area, T_{ij} is the Cauchy stress tensor, $u_{i,j}$ is the gradient of the displacements, t_i is the traction vector and δ is the variational operator [11].

In sheet metal forming, for a certain part with a fixed drawing depth, the contact pressure distribution of the work-piece provides a reference to predict the tool wear of the die. The contact pressure shows the normal stress imposed on a work-piece by the action of the die and punch. By examining the reaction stresses of a die, it can be used to assess the danger of the tool wear during the forming process.

AutoForm™ incremental module produces the contact pressure distributions of a work-piece at the die-workpiece interface to indicate the wear of the corresponding die, under various binder pressure loads and lubrication coefficients.

AutoForm™ die advisor module was used for the prediction of the tool wear location and the extent of wear, and determination of the optimal coating method of the tool. Various coating methods, such as physical vapour deposition (PVD), chemical vapour deposition (CVD) and protective coatings, including TiN, TiCN, TiAlN, hard-chrome and a-C:H, are supported by the module. This module utilised the finite element model to calculate friction work generated at contact regions between the die and workpiece [12]. Friction work is the work of friction per unit area and can be expressed as the integral of frictional shear stresses over an element as

$$A_F = \int \tau_F ds \tag{2}$$

where A_F is friction work, τ_F is the frictional shear stress at the nodes in an element and s is the sliding distance.

Wear volume w can be expressed as

$$w = \frac{k}{H} A_F \tag{3}$$

where H is the hardness of tool material and wear coefficient k was measured by experiments performed by VST Keller, a partner of AutoForm™ Engineering GmbH.

B. *Simulation Setup*

A reinforced rear suspension support of a vehicle was used as a case study (See Fig.1). The material of the part is hot rolled uncoated high strength steel. The production rate is 8 strokes per minute and production volume is 100,000. The thickness of the part is 2.5 mm. Table 1 shows the material properties of the part. Fig.2 illustrates the forming limit curve (FLC) of the part obtained from a test from the material supplier, in which the minor principal strain is along the x axis and the major principal strain is along the y axis.

Table 1 Material properties of reinforce rear suspension support

Young's module, MPa	2.07 105
Poisson's ratio	0.333
Specific weight, N/m^3	7.8 105
Strain hardening coefficient	0.13
Initial yield stress, MPa	420
Strength coefficient, MPa	766.25
Normal anisotropy	1

Fig.1 Reinforced rear suspension support

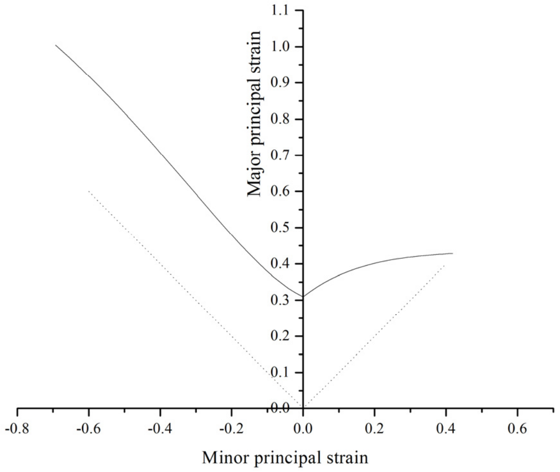


Fig.2 Forming limit curve

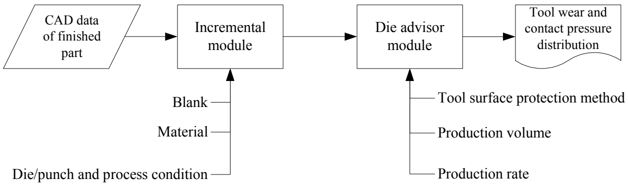


Fig.3 Simulation sequences in AutoForm™

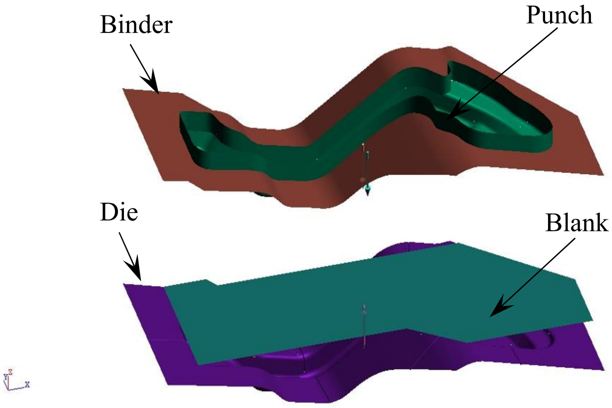


Fig.4 Blank, binder, punch and die

Fig.3 shows the sequences of simulation steps used in AutoForm™. The CAD data of finished part was imported to AutoForm™ incremental module and then meshed automatically. The blank, blinder, punch and die were then imported to the module by AutoForm™-UG interface, respectively, and placed at their specified locations according to the information obtained from the plant-site (See Fig.4). Process parameters, including lubrication coefficient and binder pressure load, as well as material parameters were defined in the incremental module. Parameters concerning the die, including tool surface protection method, production volume and production rate were then set in the die advisor module. Initial simulation was performed to find critical tool worn areas of the die. Simulations were then run for varying lubrication coefficients, binder pressure loads and tool surface protection methods to determine the influences of lubrication coefficients and binder pressure loads on the contact pressure distribution of the workpiece and the influence of coating method on the tool wear distribution of die in the critical tool worn area. The contact pressure distributions of the workpiece and tool wear distributions were obtained through the incremental module and die advisor module, respectively.

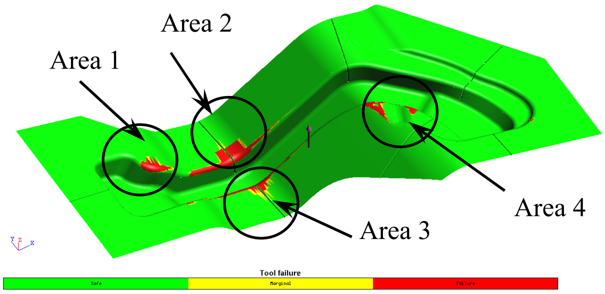


Fig.5 Potential tool worn area location on die surface obtained from initial simulation

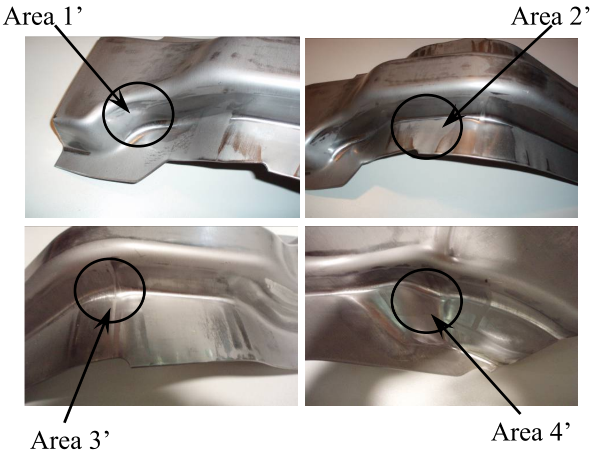


Fig.6 Photos of the worn areas on the corresponding surface of the sheet metal part

III. RESULTS AND DISCUSSION

A. *Identification of critical tool worn areas*

In the initial simulation used to determine locations of the critical tool worn area, the binder pressure load and lubrication coefficient were set as 4.5 MPa and 0.15, respectively. The initial coating method was selected as uncoated. Fig.5 plots the tool worn areas distribution obtained from the initial simulation. In Fig.5, the area with the colour close to yellow presents an area of sensitivity to tool wear, and the area with the colour close to green means an area of insensitivity to tool wear. It was concluded that Areas 1, 2, 3 and 4 were highly sensitive to tool wear, and tool wear would occur in the very early stage of the production. These areas were compared with the worn out areas of the actual surfaces of the parts produced.

Fig.6 illustrates the photos of the areas, named Areas 1', 2', 3' and 4', located on the surface of the sheet metal part, which contacted to the corresponding Areas 1, 2, 3 and 4, respectively, in the sliding movement during the sheet metal forming process. In these areas, the die is scoring off the blank. The initial predicted result is found to be in accordance with the result obtained from the plant-site.

Areas 1, 2, 3, 4 were identified as the critical tool worn area on the die surface. As the gradient in both Areas 2 and 3 was extremely large in both longitudinal and latitudinal directions, this resulted in highly increased sliding movement between the tool surface and the part surface, and accelerated the formation of worn areas in both the die surface and sheet metal blank surface. In the following discussion of contact pressure distributions, a cross-section of Area 2' and 3', named Cross-section 1, was selected as a sample (See Fig.7).

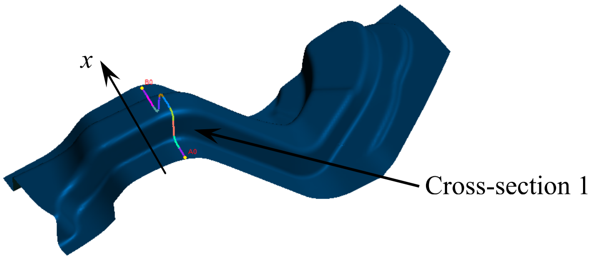


Fig.7 Cross-section 1 of Area 2' and 3'

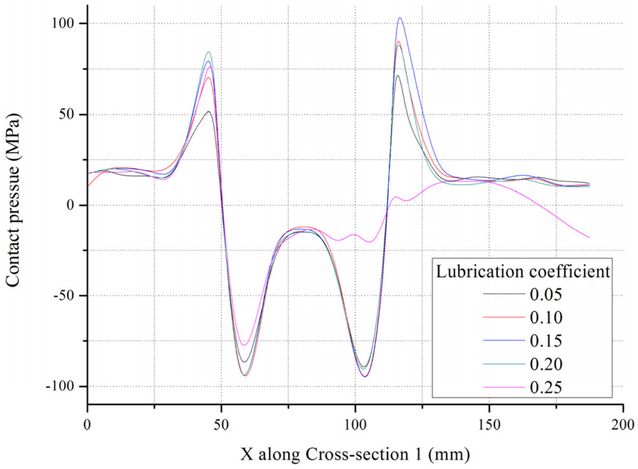


Fig.8 Contact pressure distributions upon various lubrication coefficients along Cross-section 1 (Binder pressure load is 4.5 MPa)

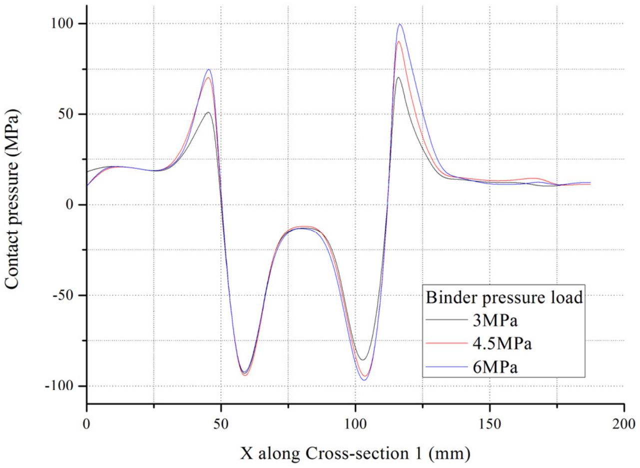


Fig.9 Contact pressure distributions upon various binder pressure loads along Cross-section 1 (Lubrication coefficient is 0.10)

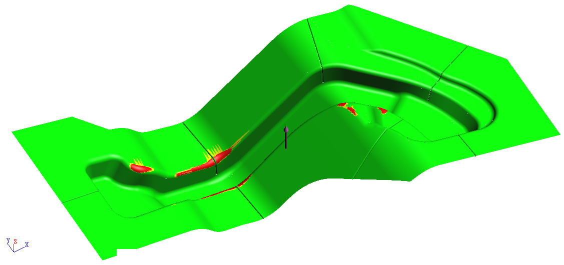
B. Comparison of contact pressure distribution for various lubrication coefficient

Fig.8 plots various contact pressure distributions under different lubrication coefficients based on the Coulomb Model. The lubrication coefficient is the dynamic friction coefficient, which indicates that the frictional force is proportional to the normal load [1]. Two positive extrema of the contact pressure along the section increased from 50 MPa to 90 MPa and from 67 MPa to 118 MPa as the lubrication coefficient rose from 0.05 to 0.15. The positive extrema were located at Area 2' and 3', which validates that Areas 2 and 3 were critical areas sensitive to the tool wear. The variation of negative positive extrema is not as significant as positive ones.

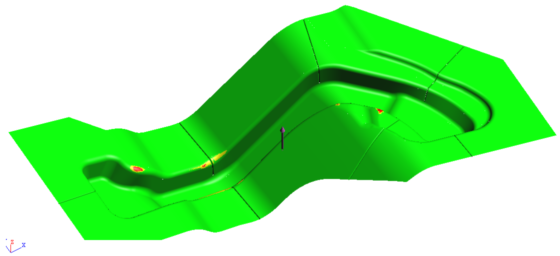
From Fig.8, it is noticed that the contact pressures at Area 3' decreased abnormally as the lubrication coefficient increased from 0.15 to 0.25. This was caused by the split of Area 3'. Area 3' began gradually splitting while the lubrication coefficient was rising from 0.20, as the dry lubrication condition blocked the smooth movement of the material flow. Considering the formability of the workpiece, lower contact pressure and qualified formability could be reached by selecting 0.10 as the lubrication coefficient.

C. Comparison of contact pressure distribution upon various binder pressure loads

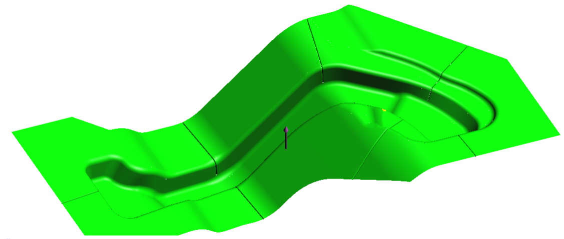
To study the contact pressure distribution under various binder pressures, 3 MPa, 4.5 MPa and 6 MPa binder pressure loads were applied in the simulation, respectively. Fig.9 shows that two positive extrema of the contact pressure along the section rose from 55 MPa to 82 MPa and from 88 MPa to 115 MPa as the pressure loads increased from 3 MPa to 6 MPa, which shows again that Areas 2 and 3 were extremely sensitive to the tool wear. The negative maximum of the contact pressure remained at approximately -90 MPa to show it was not sensitive to the variation of the pressure loads.



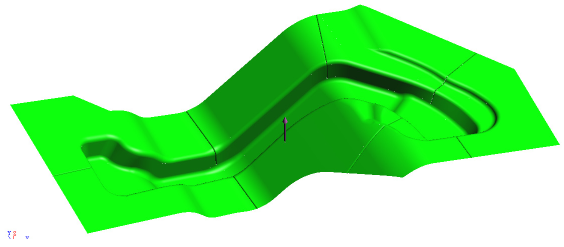
(a) PVD steel



(b) Advanced PVD steel



(c) CVD TiCTiN steel



(d) CVD Tic 3D steel

🟩 Safe 🟨 Marginal 🟥 Failure

Fig.10 Tool wear distributions upon various coating

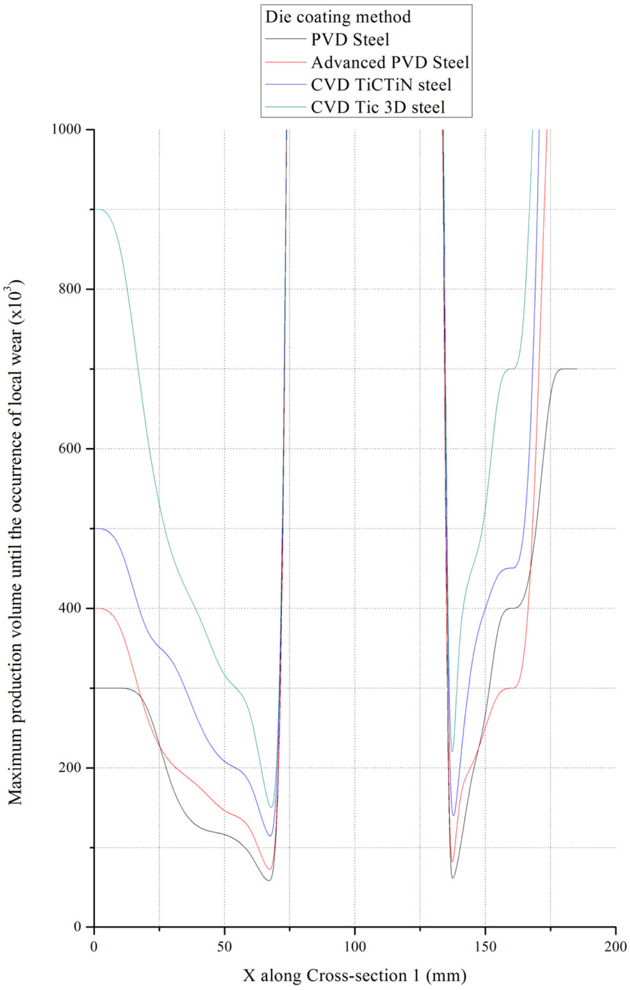


Fig.11 Maximum production volume until the occurrence of local wear along Cross-section 1 (Binder pressure load is 4.5 MPa and lubrication coefficient is 0.10)

Under the condition of the same drawing depth, the large contact pressure indicates the increased potential tool wear. However, the lower contact pressure, i.e. lower binder pressure load, results in insufficient stretch of the workpiece. To balance the tool wear and formability of the workpiece, 4.5 MPa was selected as the binder pressure load.

D. Comparison of tool wear distribution upon various die coating

Fig.10 illustrates sensitive tool worn areas on the die surface by the colour red using various coating methods. As Areas 2 and 3 were most sensitive to the tool wear, the maximum production volume until the occurrence of local wear along cross-section 1 under various die coating methods is shown in Fig.11. The binder pressure load used is 4.5 MPa and the lubrication coefficient is 0.10 in these simulations. It is noted from Fig.10 and 11 that PVD steel coating provides the least protection of the die and the local wear would appear in a short time at Areas 2 and 3 when the production volume arrived at 40K. The die surface was found to obtain high-quality protection using a CVD TiC 3D steel coating and the maximum production volume without the wear being increased to 120K. From the results of simulation, it is observed that a CVD TiC 3D steel coating was highly recommended, as it postponed the tool wear appearance to the utmost extent and extended the die-life, which could reduce the frequency of die maintenance.

IV. CONCLUSIONS

The paper investigated influences of the binder pressure load, lubrication coefficient and coating on the tool wear distribution for a certain sheet metal stamping die based on numerical simulations using AutoForm™ software. The areas that were sensitive to the tool wear were identified in the initial simulation, which were found to be in accordance with the phenomena observed from the on-site production of the actual parts. From results obtained from simulations, the lower binder pressure load, improved lubrication coefficient and coating were selected, which could reduce the likelihood of too wear. Results have shown that numerical simulation method using AutoForm™ can be used effectively in reduction of lead-time in the tool wear prediction for automobile manufacturers. Future work can be focused on the investigation of the mechanism of the tool wear, using both numerical and experimental methods.

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