Tool Wear Prediction in the Forming of Automotive DP980 Steel Sheet Using Statistical Sensitivity Analysis and Accelerated U-Bending Based Wear Test

Junho Bang 1,2, Namsu Park 1, Junghan Song 1, Hong-Gee Kim 3, Gihyun Bae 1,* and Myoung-Gyu Lee 2,*

1 Metal Forming R&D Center, Shape Manufacturing R&D Department, Korea Institute of Industrial Technology, Incheon 21999, Korea; bjh@kitech.re.kr (J.B.); nspark@kitech.re.kr (N.P.); jhsong@kitech.re.kr (J.S.)
2 Department of Materials Science and Engineering, Seoul National University, Seoul 08826, Korea
3 Materials Forming Research Group, POSCO Global R&D Center, Incheon 21985, Korea; hgkim5@posco.com
* Correspondence: baegh@kitech.re.kr (G.B.); myounglee@snu.ac.kr (M.-G.L.); Tel.: +82-32-850-0318 (G.B.); +82-2-880-1711 (M.-G.L.)

Abstract: The forming process of ultra-high-strength steel (UHSS) may cause premature damage to the tool surface due to the high forming pressure. The damage to and wear of the tool surface increase maintenance costs and deteriorate the surface quality of the sheet products. Hence, a reliable prediction model for tool wear can help in the efficient management of the quality and productivity of formed sheet products of UHSS. In this study, a methodology is proposed for predicting the wear behavior of stamping tools that are used in the forming process of DP980 steel sheet. Pin-on-disk tests were conducted based on the Taguchi method to develop the tool wear prediction model. Using statistical analysis based on the signal-to-noise (S/N) ratio and ANOVA result, the contact pressure and the sliding distance were selected as the major contact parameters for tool wear. The Archard wear model has a limitation in predicting the nonlinear behavior of tool wear. Therefore, the power-law nonlinear regression model as a function of the contact pressure and the sliding distance was constructed. To verify the reliability of the constructed tool wear prediction model, the U-draw bending tests were designed. The modified U-draw bending test, which accelerates tool wear, is newly designed to evaluate the tool wear for different contact pressures and sliding distances. The modified die generated a contact pressure four times higher than that of the conventional die from the finite element (FE) simulation results. The tool wear prediction model was validated by comparing the predicted results with the experimental results of DP980 sheets formed using the physical vapor deposition (PVD) CrN-coated STD11 tool steel.

Keywords: abrasive wear; tool wear prediction; ultra-high-strength steel (UHSS); pin-on-disk test; Taguchi method; power-law nonlinear regression model; accelerated U-bending wear test

1. Introduction

The demand for weight reduction in an auto-body has been continuously increasing in the automotive industry over recent years. For this purpose, non-ferrous metal sheets, such as carbon-fiber-reinforced plastics (CFRPs), and magnesium and aluminum alloys have been regarded as alternatives to conventional steel sheets owing to their low density and high specific stiffness compared to steel. Nevertheless, steel sheets are still the major material candidates for car body design due to their low cost and eco-friendly manufacturing process, in addition to efficient control over their strength and ductility using properly designed heat treatments. These materials are effective in improving fuel efficiency and crashworthiness. For example, Li et al. [1] proposed a typical method for lightweighting by applying thinner and higher strength steel sheets to automotive parts based on the simulation of the body part impact while satisfying crashworthiness. Steel makers have been developing a variety of ultra-high-strength steel (UHSS) sheets that are...
have been developing a variety of ultra-high-strength steel (UHSS) sheets that are applicable to the lightweight design of auto-bodies by reducing the sheet thickness. As a result, the proportion of UHSS in the auto-body tends to increase to satisfy the strengthened regulations regarding carbon emission and passenger safety.

UHSS generates tremendous stamping pressure on the tool surface owing to its higher strength compared to conventional steel sheets. Therefore, tool damage such as galling, chipping, and cracking occurs due to the frictional resistance between the sheet metal and the tool surface in the cold stamping process, noted by Carlsson [2] and shown in Figure 1 [3]. These defects lead to numerous problems in surface quality, geometric accuracy, maintenance cost, and productivity. To overcome these problems, special heat treatments and surface coatings should be applied to the tool surface to improve wear resistance. However, this may increase the overall manufacturing cost.

To improve productivity and reduce maintenance costs, process management based on the accurate prediction of tool wear is required. However, the sheet metal forming process involves various parameters such as lubrication, binder force, tool geometry and contact characteristics. All of which affect tool wear. Therefore, establishing reliable tool management that relies solely on wear experiments based on trial-and-error and the engineer’s experience is very challenging and increases both time and cost. To overcome these challenges, numerous research studies have been performed to understand the contact and wear mechanisms by using numerical modeling and simulations. Podra and Andersson [4] analyzed a conical spinning contact considering surface topography both experimentally and with simulation and proposed a modeling and simulation procedure. Kim et al. [5] verified the simulation accuracy of the wear depth in the block-on-ring experiment considering the continuous wear propagation. Lengiewicz and Stupkiewicz [6] proposed a computationally efficient model for wear evolution based on the Archard wear model and verified with the pin-on-disk test problem modeled by three-dimensional finite elements.

Some researchers have tried to develop methodologies for predicting the tool wear behavior in the actual manufacturing processes. For the metal cutting operation, Yen et al. [7] proposed a methodology to predict the tool wear evolution over long cutting periods in the cutting process based on the finite element (FE) analysis. Binder et al. [8] applied the FE-based tool wear simulation method combined with the modified Usui tool wear model in order to predict the wear behavior of the coated cutting tool with a complex shape. Binder et al. [9] extended the constructed simulation method to the tool and process design for accurate tool wear prediction in metal cutting. Pimenov et al. [10] developed a simulation model of stress conditions for the flank wear on the tool’s flank surface using the stress intensity equation. They used FE modeling to simulate the evolutionary behavior of tool wear over a long cutting period and adapted the wear rate equation for estimating tool wear for a three-dimensional simulation that considered changes in local thermal,
frictional, and wear properties. For the tool wear evaluation of the forging process, the Archard wear model [11] is usually used to the FE-based simulation for predicting the wear behavior of the forging tool. Lee and Jou [12] applied the Archard wear model considering the temperature-dependent hardness of warm forging tools for predicting the wear amount of the forging die. Behrens and Schaefer [13] also used a similar approach for the wear prediction of hot forging tools. They concluded that the Archard wear model shows good performance in predicting the wear phenomenon of warm and hot forging dies. The Archard wear model has been also used to predict the wear behavior of the stamping die in the sheet metal forming process. Hoffmann et al. [14] established an advanced simulation method using the Archard wear model and the geometry update scheme for the sheet metal forming process of the B-pillar reinforcement component. Hoffmann and Nurnberg [15] suggested a new approach to investigate the quantitative tool wear depth in the cylindrical cup drawing process and evaluated the tool wear for various grades of automotive steel sheets. As mentioned above, most wear simulations have adopted the Archard model, considering its efficiency and simplicity. Because the Archard model has reported that the wear amount is linearly proportional to the contact pressure and the sliding distance, there is a limitation in the prediction accuracy of nonlinear evolutionary behaviors of wear. Some researchers have presented the power-law-type prediction models expressed as a function of normal load and sliding distance to improve the prediction accuracy of the wear behavior. Rhee [16] proposed a power law empirical wear equation for predicting the weight loss of the asbestos-reinforced polymers sliding against metal surfaces. Bayer [17] also used the power law equation for developing a general model of surface wear mechanisms for both abrasive and adhesive wear. Hsu et al. [18] summarized various wear models for metals, including the power law equation and complicated equations based on the wear mechanism map. These research results support the idea that a power-law-based wear model can provide improved results for the nonlinear evolutionary wear behavior in the metal forming process. Although power-law-based wear models have improved prediction accuracy compared to the conventional Archard-based models, there are insufficient studies on modeling the wear of tool dies used in the stamping of automotive steel sheets, particularly UHSS sheets. Eriksen [19] reported that tool wear is generally due to the abrasive wear mechanism that causes geometrical changes over the die edge for the deep drawing process.

The aim of this study is to propose a new methodology to predict the abrasive wear behavior of stamping tools for dual-phase (DP) steel with the strength of 980 MPa. The power law wear model is implemented in this study to improve the predictive capability for the estimation of abrasive tool wear. First, a pin-on-disk test was performed to analyze the wear behavior and obtain an experimental database for developing the tool wear prediction model. Then, the Taguchi method was employed for an efficient and systematic experimental design. The sensitivity analysis was performed using the signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) result to select the main control parameters affecting the wear behavior. Based on these results, the parameters of the power-law-based tool wear model were identified with selected major control parameters. Finally, the reliability of the tool wear prediction model was verified by comparing the predicted results of the conventional and modified dies for the drawing test with experimental results.

2. Materials and Tool Wear Characteristics

The contact characteristics acting on the tool surface in the sheet metal forming process were identified through numerical simulations. A B-pillar (or central pillar) of an automobile was used to investigate the range of contact pressure and position where the tool wear is mostly expected. The material used in this study is DP980 steel sheet with the thickness of 1.4 mm, which is produced by POSCO Gwangyang steelworks in South Korea. The mechanical properties are listed in Table 1, which are measured by MTS 810 (MTS Systems Corporation, Eden Prairie, MN, USA). The FE simulation was performed using the dynamic explicit software PAM-STAMP v2017.0 (ESI-Group, Rungis, France).
To improve the simulation procedure, Hill’s 48 yield function with isotropic hardening law was assumed. As the amount of tool wear increases, the friction coefficient at the contact interfaces between the sheet and tool surfaces does not change noticeably [20,21]. Therefore, the Coulomb friction coefficient was selected as 0.15, which showed good correlation between the experiment and the numerical simulation [22]. The tool was discretized by rigid shell elements because the elastic deformation of the tool has no significant effect on the contact pressure, as reported by Erosoy-Nurnberg et al. [23]. The blank was modeled with deformable shell elements. The element size at the contact interface between the blank and the tool has to be sufficiently fine to predict the accurate contact pressure. Mesh refinement was used because the smaller the mesh size, the higher the computation time. The initial mesh size was 10 mm, and the mesh refinement method was set to 5 levels so that the minimum mesh size was 0.625 mm. Stamping simulation was performed by Inter Core i7-6700 (8.0 GB of RAM). The computation took about 6 h. Figure 2 shows the contact pressure distribution after the forming process of the B-pillar. The simulation results indicate that the maximum contact pressure of 1.85 GPa was predicted at the sharp curvature of the tool. The potential wear locations due to high contact pressure could be confirmed from the observation of a real stamping tool for the same B-pillar. The preliminary simulation and experimental analysis indicated that the contact pressure was the most significant factor affecting the tool wear. Based on the simulation results, the experimental conditions of the pin-on-disk tests were established for developing a tool wear prediction model of DP980.

### Table 1. Mechanical properties of a DP980 steel sheet obtained from the tensile test.

| Thickness (mm) | YS 1 (MPa) | UTS 2 (MPa) | Swift Hardening Law \( \sigma = k(\varepsilon_0 + \varepsilon)^n \) | R-Value |
|---------------|------------|-------------|-------------------------------------------------|---------|
| 1.4           | 721.6      | 1042.0      | \( k = 1499.11 \) \( \varepsilon_0 = 0.00108 \) \( n = 0.107 \) | 0°: 0.956 45°: 0.996 90°: 1.098 |

1 YS: yield stress; 2 UTS: ultimate tensile stress.

![Figure 2](image-url) Contact pressure distribution in the stamping simulation of the B-pillar with a DP980 steel sheet.

### 3. Tool Wear Prediction Model

#### 3.1. Experimental Setup for a Pin-on-Disk Test

A pin-on-disk test is the most widely used experimental method to analyze wear characteristics quantitatively according to the process parameters and environmental conditions. In this study, this test method was used to estimate the quantitative amount of wear to develop a wear prediction model for DP980 steel sheets. Figure 3 shows the pin-on-disk tester comprising of the pin, the disk, and a weight. The TRB3 Tribometer (CSM Instruments SA, Peseux, Switzerland) was used as the testing machine. The pin comes in contact with the metallic disc with a designated normal force applied by a weight, and wear
occurs at the contact interface between the static pin and the rotating disk during the test. The pin was prepared using the same processing conditions as that for the B-pillar dies. The material was STD (Steel Tool Dies)-11 tool steel with proper heat treatment, which is produced by POSCO Pohang steelworks in South Korea. As shown in Figure 4, quenching heat treatment was used to harden the STD11 tool steel by introducing the martensite microstructure. The heat treatment includes multiple heating processes at temperatures of 600, 850, and 1030 °C, for 90 min at each temperature, which was followed by a two-step tempering treatment for 2 h to reduce the brittleness arising from the quenching process standardized in KS D 3753 [24]. The Vickers hardness HV0.1 of the STD11 tool steel (pin) was 787.9 ± 13.5, measured at a normal force of 0.1 kgf. The Vickers hardness of DP980 steel is about 320 Hv, as reported by Farabi et al. [25]. The pin surfaces were coated with CrN using the physical vapor deposition (PVD) method. The wear test was performed according to various contact parameters using this experimental setup. The chemical composition of the DP980 steel sheet and STD11 tool steel is presented in Table 2.

Figure 3. Experimental setup of the pin-on-disk test: (a) testing machine; (b) geometry and dimension of the pin and the disk.

Figure 4. Heat treatment conditions of the pin, consisting of quenching (left) and temperature (right).

Table 2. Chemical composition of the DP980 and STD11 steel (wt%).

| Steel   | C   | Mn  | Si  | Al  | Cr  | Ni  | N   | Fe  | Mo  | V   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| DP980   | 0.15| 1.45| 0.33| 0.05| 0.02| 0.01| 0.009| Balance | - | -   |
| STD11   | 1.55| 0.30| 0.26| -   | 11.36| -   | -   | -   | 0.81| 0.20|
3.2. Experimental Design Parameters

An efficient experimental design method is required to construct a reliable wear prediction equation. In this study, the Taguchi method presented by Taguchi and Konishi [26] was used for the experimental design of the pin-on-disk test with various parameters. This method is a powerful and widely used design scheme in engineering analysis because a small number of experimental cases can be used to evaluate the response of control parameters and experimental results in the design space.

To formulate a tool wear prediction model, an orthogonal array should be constructed by investigating the actual sheet metal forming process. Pereira et al. [27] reported that the contact pressure and the sliding distance are essential for evaluating the wear behavior and lifetime of the tool. Rhee [16] confirmed that the sliding velocity can be an important parameter in constructing an empirical wear equation. Based on references, the contact pressure, the sliding distance, and the velocity were selected as the major factors affecting the wear behavior. For three contact parameters, an orthogonal array L25 (5^3) can be used for the experimental design of the pin-on-disk test. The range of the contact parameters should be confirmed for constructing the orthogonal array.

In the previous section, the maximum contact pressure of the B-pillar predicted by the FE simulation was 1.85 GPa, as shown in Figure 2. For the pin-on-disk test, the contact pressure should be transformed into a normal force. Therefore, the normal force corresponding to this contact pressure was calculated and set as the force range of the pin-on-disk test. Because the tool structure is in the range of the elastic deformation during the sheet metal forming process [28,29], the normal force acting on the contact surface was derived using the Hertz contact theory [30]. The Hertz contact theory states that when two elastic bodies are loaded by contact, elastic bodies create a contact area in which the contact pressure is distributed. As shown in Figure 5, the elastic sphere of radius $R$ is indented to a depth $d$, which induces a contact surface of radius $a$.

$$a = \sqrt{Rd}$$

\[1\]

![Figure 5. Schematic diagram of the contact between an elastic sphere and sheet.](image)

The depth $d$ is generated by the applied normal force.

$$F = \frac{4}{3} E_r R \frac{1}{2} d^2$$

\[2\]

where $E_r$ is the reduced elastic modulus, which can be calculated as follows:

$$\frac{1}{E_r} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2}$$

\[3\]
where \( \nu_1 \) and \( \nu_2 \) are Poisson’s ratios and \( E_1 \) and \( E_2 \) are the elastic moduli for the elastic bodies denoted by subscripts 1 and 2, respectively, in Figure 5. The distribution of the contact pressure acting on the elastic body \( p \) is expressed as a function of the distance \( r \) from the center of the circle at the contact area.

\[
p(r) = p_0 \left(1 - \frac{r^2}{a^2}\right)^{1/2}
\]

where \( p_0 \) is the maximum contact pressure, which is applied at the center of the contact surface, as reported by Johnson [31].

\[
p_0 = \frac{3F}{2\pi a^2}
\]

The radius of the contact surface is given by

\[
a^3 = \frac{3FR}{4E_r}
\]

In this study, elastic bodies 1 and 2 are the CrN coating of the pin and the DP980 steel sheet, respectively. Ichimura and Ando [32] measured the elastic modulus of CrN coating (\( E_1 \)), which can be determined to be 375 GPa. Poisson’s ratio of the CrN coating (\( \nu_1 \)) is selected as 0.28, obtained from Fabis et al. [33]. The elastic modulus of the DP980 steel sheet (\( E_2 \)) and Poisson’s ratio of the DP980 steel sheet (\( \nu_2 \)) are 210 GPa and 0.3, respectively, which are the general elastic properties of the steel sheet. As shown in Figure 6, an analytical solution for the normal force is calculated as a function of the contact pressure by using the Hertz contact theory. From this result, the normal force equivalent to the contact pressure of 1.85 GPa was calculated as 9.50 N for the given geometry of the pin. Therefore, a maximum normal force of 10.0 N was selected for the pin-on-disk test.

![Figure 6. A normal force vs. contact pressure curve by the Hertz contact theory.](image)

The mechanical press is generally used for the sheet metal forming process of the B-pillar. The conventional stamping speed is approximately 10 spm in the B-pillar mass production process, and the maximum forming velocity is approximately 180 mm/s, considering the sliding motion of the sheet metal. Therefore, the maximum sliding velocity was set to 188.4 mm/s (120 rpm), with a rotation radius of 15 mm. The sliding distance was selected as 1000 revolution (94.20 m) for sufficient tool wear to occur. Table 3 shows the levels of the three contact parameters based on the above maximum test values. From these values, an orthogonal array \( L_{25} (5^3) \) can be constructed as shown in Table 4.
Table 3. Contact parameters and factor levels for a pin-on-disk test.

| Contact Parameters        | Level 1         | Level 2         | Level 3         | Level 4         | Level 5         |
|---------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Normal force, F           | 2 N (1.104 GPa) | 4 N (1.391 GPa) | 6 N (1.592 GPa) | 8 N (1.752 GPa) | 10 N (1.887 GPa) |
| Sliding velocity, V       | 120 rpm         | 100 rpm         | 80 rpm          | 60 rpm          | 40 rpm          |
| Sliding distance, L       | 1000 rev. (94.20 m) | 800 rev. (75.36 m) | 600 rev. (56.52 m) | 400 rev. (37.68 m) | 200 rev. (18.84 m) |

Table 4. Taguchi orthogonal array L<sub>25</sub>(5<sup>3</sup>) and pin-on-disk test results in design cases.

| Run  | Normal Force F (N) | Sliding Velocity V (rpm) | Sliding Distance L (rev.) | Pin Wear Depth h (µm) | Pin Volume Loss V<sub>loss</sub> (mm<sup>3</sup>) |
|------|--------------------|--------------------------|--------------------------|-----------------------|-----------------------------------------------|
| 1    | 10                 | 120                      | 1000                     | 15.1 ± 1.3            | 2.136 ± 0.350                               |
| 2    | 10                 | 100                      | 800                      | 14.9 ± 3.8            | 2.085 ± 0.509                               |
| 3    | 10                 | 80                       | 600                      | 11.5 ± 1.0            | 1.214 ± 0.215                               |
| 4    | 10                 | 60                       | 400                      | 11.3 ± 1.5            | 1.206 ± 0.345                               |
| 5    | 10                 | 40                       | 200                      | 5.6 ± 1.0             | 0.299 ± 0.690                               |
| 6    | 8                  | 120                      | 800                      | 12.5 ± 2.3            | 1.467 ± 0.453                               |
| 7    | 8                  | 100                      | 600                      | 11.9 ± 0.5            | 1.326 ± 0.128                               |
| 8    | 8                  | 80                       | 400                      | 8.9 ± 0.5             | 0.744 ± 0.059                               |
| 9    | 8                  | 60                       | 200                      | 5.1 ± 0.7             | 0.288 ± 0.035                               |
| 10   | 8                  | 40                       | 1000                     | 17.5 ± 0.5            | 2.868 ± 0.191                               |
| 11   | 6                  | 120                      | 600                      | 9.6 ± 0.9             | 0.876 ± 0.085                               |
| 12   | 6                  | 100                      | 400                      | 8.1 ± 1.0             | 0.615 ± 0.081                               |
| 13   | 6                  | 80                       | 200                      | 6.4 ± 0.5             | 0.392 ± 0.050                               |
| 14   | 6                  | 60                       | 1000                     | 15.7 ± 2.2            | 2.326 ± 0.356                               |
| 15   | 6                  | 40                       | 800                      | 13.3 ± 0.4            | 1.666 ± 0.110                               |
| 16   | 4                  | 120                      | 400                      | 8.0 ± 1.2             | 0.600 ± 0.064                               |
| 17   | 4                  | 100                      | 200                      | 4.8 ± 1.1             | 0.215 ± 0.037                               |
| 18   | 4                  | 80                       | 1000                     | 9.8 ± 1.6             | 0.911 ± 0.051                               |
| 19   | 4                  | 60                       | 800                      | 7.3 ± 1.0             | 0.496 ± 0.084                               |
| 20   | 4                  | 40                       | 600                      | 6.5 ± 2.1             | 0.394 ± 0.097                               |
| 21   | 2                  | 120                      | 200                      | 3.8 ± 0.4             | 0.139 ± 0.019                               |
| 22   | 2                  | 100                      | 1000                     | 7.3 ± 1.2             | 0.507 ± 0.085                               |
| 23   | 2                  | 80                       | 800                      | 5.4 ± 1.7             | 0.274 ± 0.029                               |
| 24   | 2                  | 60                       | 600                      | 4.6 ± 0.2             | 0.197 ± 0.023                               |
| 25   | 2                  | 40                       | 400                      | 5.5 ± 1.4             | 0.281 ± 0.019                               |

3.3. Measurement of Pin Wear Depth

The pin-on-disk test was performed in various experimental conditions based on the orthogonal array constructed in the previous section. Three repetitive tests were performed for all design cases. After the pin-on-disk tests, the tool wear areas were measured with an optical electron microscope (OEM) ECLIPSE MA200 (Nikon, Tokyo, Japan), as shown in Figure 7. From the tool wear area, the wear scar diameter <i>d_w</i> can be obtained by assuming the measured wear area of the pin as a circle standardized in ASTM (American Society for Testing and Materials) G99-17 [34].

\[ A_p = \frac{\pi d_w^2}{4} \]  \quad (7)

Then, the tool wear depth <i>h</i> is related to the wear scar diameter <i>d_w</i> as follows:

\[ h = r_p - \left( r_p^2 - \left( \frac{d_w}{2} \right)^2 \right)^{\frac{1}{2}} \]  \quad (8)

where <i>r_p</i> is the pin end radius.
By using the following equation, the pin volume losses \( V_{\text{loss}} \) can be calculated from the wear scar diameter \( d_w \) and the tool wear depth \( h \) derived from the previous equations.

\[
V_{\text{loss}} = \frac{\pi h}{6} \left( \frac{3d_w^2}{4} + h^2 \right)
\]  

(9)

In Table 4, the measured wear depth \( h \) and pin volume loss \( V_{\text{loss}} \) are listed for all experimental design cases. In general, the coating thickness of CrN for the stamping die is approximately 10 \( \mu \)m. The test range of the pin-on-disk is well designed to evaluate the wear amount considering the CrN coating thickness.

![Figure 7. Wear area analysis of the pin measured by an optical electron microscope (OEM; \( F = 8\) N, \( V = 60\) rpm, \( L = 200\) rev.).](image)

**3.4. Sensitivity Analysis of Wear Parameters**

The S/N ratio and the ANOVA result were used to check the significant control factors affecting the wear characteristics of the tool. The S/N ratio was used to determine the robustness of the control factors of the product or process. It measures how the response changes relative to the target values under various noise conditions. The performance characteristics can be quantified in terms of the respective response to noise and signal factors. During the response analysis, the deviation between the experimental value and the desired value can be computed using the loss function and converted into the S/N ratio. There are three kinds of S/N ratios for analyzing and identifying performance characteristics, depending on the objective of the experiments: higher-the-better, lower-the-better, and nominal-the-best [35]. Among them, the higher-the-better ratio is suitable for evaluating the characteristics of the tool wear problem because tool wear shows an increasing tendency according to the contact parameters. The S/N ratio \( \eta \) is calculated as follows:

\[
\eta = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right)
\]  

(10)

where \( y_i \) is the data measured in the \( i \)-th experiment and \( n \) is the total number of experiments. As you can see from Figure 8, both pin wear depth and pin volume loss show variation in the higher-the-better ratio with respect to the contact parameters. From this figure, it was confirmed that the sliding velocity might not be a significant factor in the current tool wear during the investigated forming process.

The ANOVA is another sensitivity analysis method to evaluate the statistical significance of independent variables that generate variance in dependent variables. It is used to identify the relationship between independent and dependent variables. Table 5 shows the ANOVA results of the pin wear depth and the pin volume loss according to the three contact parameters. The F-value represents the significance level of the control factors. The \( p \)-value can also be used to check the significance of control factors with the criterion of 0.05 for the 95% confidence level. This table also indicates that the sliding velocity is a statistically insignificant factor for both pin wear depth and pin volume loss, as the F-value of the sliding velocity is relatively much smaller than that of other contact parameters.
Moreover, the p-value is also larger than 0.05. Therefore, it was concluded that the sliding velocity can be excluded for developing the prediction model because of its negligible effect on wear behavior.

![Figure 8. Effect of control factors on the signal-to-noise (S/N) ratio for (a) pin wear depth and (b) pin volume loss.](image)

**Table 5. Results of ANOVA for pin wear depth.**

| Variance Source | Degree of Freedom (DOF) | Adjusted Sums of Squares (Adj. SS) | Adjusted Mean Squares (Adj. MS) | F-Value | p-Value |
|-----------------|------------------------|------------------------------------|---------------------------------|---------|---------|
| Pin wear depth  | Normal force (F)        | 4                                  | 156.083                         | 39.021  | 11.52   | 0.000   |
|                 | Sliding velocity (V)    | 4                                  | 6.705                           | 1.676   | 0.49    | 0.740   |
|                 | Sliding distance (L)    | 4                                  | 168.735                         | 42.184  | 12.45   | 0.000   |
|                 | Error                  | 12                                 | 40.662                          | 3.388   | -       | -       |
|                 | Total                  | 24                                 | 372.185                         | -       | -       | -       |
| Pin volume loss | Normal force (F)        | 4                                  | 5 × 10^-4                       | 1 × 10^-6 | 6.72   | 0.004   |
|                 | Sliding velocity (V)    | 4                                  | 0                               | 0       | 0.59    | 0.677   |
|                 | Sliding distance (L)    | 4                                  | 6 × 10^-4                       | 2 × 10^-6 | 8.20   | 0.002   |
|                 | Error                  | 12                                 | 2 × 10^-6                       | 0       | -       | -       |
|                 | Total                  | 24                                 | 1.3 × 10^-5                     | -       | -       | -       |

3.5. Tool Wear Prediction Model

The tool wear prediction model was constructed by approximating the pin-on-disk test results for various design cases generated by the Taguchi method. The normal force was converted again into contact pressure because the measured value for tool wear prediction in the numerical simulation is the local contact pressure. After excluding the sliding velocity based on the statistical sensitivity analysis described in the Section 3.4, the tool wear depth was formulated by the power law equation as follows:

\[
h = K P^\alpha L^\beta (\mu m)
\]  \( (11) \)

where \( P \) and \( L \) are the contact pressure and the sliding distance, respectively, and \( K, \alpha, \) and \( \beta \) are model constants. From the fitting of the proposed power law model to the experimental data, the exponents of the contact pressure and the sliding distance are \( \alpha = 1.7570 \) and \( \beta = 0.5073 \), respectively, and the parameter \( K = 0.01661 \) for the investigated DP980 steel and tool material. The identified model parameters show that the contact pressure is a more sensitive parameter to the tool wear than the sliding distance. To verify the reliability of the tool wear prediction model, the comparison between the measured and predicted wear depths was examined for each run of the orthogonal array \( L_{25} \) (5^3) as shown in Figure 9. The least-squares \( R^2 \) value and \( R^2_{\text{Adj}} \) value in the estimation of the tool wear depth were found to be 87.01% and 86.15%, respectively, which indicates a high level of linear relationship between the measured and predicted results. Thus, the power law equation is a suitable formulation to develop the tool wear prediction model.
Figure 9. Prediction accuracy of the wear depth calculated by the power-law-type equation.

4. Verification of Tool Wear Using the U-Draw Forming Process

The U-draw bending test was adopted to evaluate the wear amount during the drawing process. A modified punch shape was designed by numerical simulation to cause contact pressure localization and accelerate tool wear. Based on the conventional and modified tool shapes, the drawing wear tests were performed to investigate the actual wear behavior according to the die contact pressure and the sliding distance. Finally, the tool wear prediction model was verified by comparing the tool wear depth obtained from the experiments in terms of the angle of the die radius.

4.1. Drawing Tool Design by Numerical Simulation

A numerical simulation was performed for the conventional U-draw bending test to investigate the contact conditions during the test. The simulation was performed using PAM-STAMP v2017.0 (ESI-Group, Rungis, France). For simulation efficiency, a half model was constructed by applying the symmetric conditions of the tool and material properties. The tool was modeled with rigid elements because the elastic deformation of the die has little effect on the contact pressure, as reported by Ersoy-Nurnberg et al. [23]. The blank was discretized by deformable solid elements with three layers. As shown in Figure 10, fine meshes were applied in the contact interface between the tool and the blank to predict the contact pressure more accurately at the interface by excluding the mesh size effect. However, finer meshes increase the computation time. After optimizing the mesh sizes of the simulations, the determined element sizes of the tool and the blank were 750,000 and 53,988, respectively. The same blank material from the previous section was used again, and its mechanical properties are summarized in Table 1.

The friction coefficient between the tool and the blank was selected as 0.15, which achieved good correlation between the experiment and the numerical simulation, reported by Pereira et al. [22]. In the numerical simulation, the contact pressure distribution was observed during a punch stroke of 40 mm at the die shoulder where a severe contact pressure occurred. Figure 11a shows the contact pressure distribution according to the punch stroke along the die shoulder. Figure 11b,c shows the maximum contact pressure and its location with respect to the punch stroke. For the conventional die, the maximum contact pressure stabilizes after the 12 mm punch stroke. The peak and stabilized values were 0.940 and 0.502 GPa, respectively. From this result, it can be noted that the conventional drawing test has a limitation for describing the severe contact condition of the DP980 for a B-pillar. Therefore, a modified die design is required to generate a higher contact pressure.
A new die design was proposed for generating a higher contact pressure than the conventional U-draw bending test. To introduce a more severe contact condition, a small bead with a height of 0.1 mm was added at the die angle of 59°, where the peak contact pressure of the conventional die occurs. A similar level of contact pressure was generated at the start regions of the die radius. Then, the modified die resulted in a higher contact pressure at the bead position, unlike the conventional die. The maximum contact pressure of the modified die was 1.866 GPa, as presented in Figure 11b. This value is similar to the contact pressure investigated in the forming simulation of the B-pillar. Figure 11c also confirms the position of the maximum contact pressure after stabilization. The simulation results indicate that the modified die design is effective for describing the severe contact behavior of UHSS.

4.2. Drawing Wear Test

The drawing wear test was performed using the conventional and modified U-bending dies proposed by the numerical simulation. The geometric and process parameters represent a typical sheet metal stamping operation that is commonly prone to wear. The
test configuration is summarized in Table 6, which was reported from Weiss et al. [36]. Figure 12 shows the experimental setup and schematic diagrams of the drawing wear test. It was designed as an insert-type tool for efficient measurement of the wear profile on the tool surface. The tool was made using STD11 tool steel and heat-treated under the same conditions as the pin of the pin-on-disk tester, as shown in Figure 3. The tool surface was coated by the PVD method with CrN to improve the wear resistance. The coating thickness was measured using the OEM ECLIPSE MA200 (Nikon, Tokyo, Japan), and it was approximately 9.9 μm, as shown in Figure 13. The Vickers hardness HV0.1 of the PVD CrN-coated layer was 2137.6 ± 35.7, measured at a normal force of 0.1 kgf.

Table 6. Geometric and process variables for the drawing wear test [36].

| Parameter                  | Description | Value   |
|----------------------------|-------------|---------|
| Punch width                | wp          | 30 mm   |
| Draw depth                 | D           | 40 mm   |
| Blank holding force        | fh          | 12.5 kN |
| Die-to-punch gap           | G           | 1.54 mm (10% clearance) |
| Blank length               | L           | 150 mm  |
| Die corner radius          | rd          | 5 mm    |
| Punch corner radius        | rp          | 5 mm    |
| Blank thickness            | t           | 1.4 mm  |
| Blank width                | wb          | 26 mm   |

Figure 12. Experimental setup and schematic diagrams of the drawing wear test: (a) drawing wear test; (b) initial setup for the drawing test; (c) after forming stroke.
The experiments with the conventional die performed 5000 hits to wear out the PVD CrN-coated layer. The modified die only required 2500 hits because of the higher contact pressure. The tool surface at the centerline of the die shoulder was observed using the OEM ECLIPSE MA200 (Nikon, Tokyo, Japan) to confirm the wear state of the tool surface. It was observed segmentally at an interval of 10° in the area of interest. A 10× optical lens was used to magnify the tool surface. The individual photographs were attached together to create a complete view of the die radius surface. Figure 14 shows the amount and locations of scratches captured on the die radius surface after the wear test. For the conventional die, the scratches (or defects on the surface) mostly occurred at the start of the die radius, where a 0.50 GPa contact pressure was applied on the die radius of 7.5° for a long distance, as shown in Figure 11. In the case of the modified die, it was found that the coating layer was completely worn out, and the boundary between the coating layer and the tool material could be observed at the die angle of 59.0°, where a pressure of 1.866 GPa was applied for a long time, as shown in Figure 11. The worn surface of the modified die at the die angle of 59.0° was further observed by OEM. Microscratches were observed at the worn surface, which were parallel to the sliding direction, as shown in Figure 15. It was found that the tool wear in the sheet metal forming process was generally due to abrasive wear. The observed results confirm again that the contact pressure and the sliding distance are the contact parameters that have a significant influence on the tool wear behavior.

The wear depths for the conventional die and the modified die were quantitatively measured to estimate the wear behaviors of the respective tool surfaces. The tool wear behavior was evaluated by analyzing the relationship between the measured wear depth and the contact condition of the respective tool surface. The tool wear depth was measured using Leitz Infinity 12.10.6 (Hexagon AB, Stockholm, Sweden), which is a contact-type three-dimensional measuring instrument capable of recognizing relative coordinates with a precision of 0.3 + L/1000 [µm] (L = mm). First, the relative coordinates were recognized in the area where the tool wear did not occur. Next, the wear depth was measured by the absolute difference of the surface profile at the wear occurrence position before and after the wear test. As shown in Figure 16a, the relative coordinate was recognized at the blue dashed line where there was no contact with the blank. Subsequently, the origin of the coordinate was generated. Based on the origin of the coordinate, the tool surface profile was recognized by measuring the solid red line, which is the centerline of the tool, in contact with the blank during the drawing process. As shown in Figure 16b, the point data were measured along with the profile of the tool surface and each point was connected using the spline option in AUTOCAD 2020 (Autodesk, Inc., San-Rafael, CA, USA).
The maximum wear depth of the conventional die was 2.25 µm at a die angle of 17°. For the modified die, the wear depth drastically increased up to 10.42 µm because of the high contact pressure. The wear location also moved to the die angle at approximately 59°. From this result, the drawing wear test condition was established successfully to induce the high contact pressure predicted by the numerical simulation.

![Figure 13](image1.png)

**Figure 13.** Measurement of the CrN-coated layer thickness by OEM.

The experiments with the conventional die performed 5000 hits to wear out the PVD CrN-coated layer. The modified die only required 2500 hits because of the higher contact pressure. The tool surface at the centerline of the die shoulder was observed using the OEM ECLIPSE MA200 (Nikon, Tokyo, Japan) to confirm the wear state of the tool surface. It was observed segmentally at an interval of 10° in the area of interest. A 10 × optical lens was used to magnify the tool surface. The individual photographs were attached together to create a complete view of the die radius surface. Figure 14 shows the amount and locations of scratches captured on the die radius surface after the wear test. For the conventional die, the scratches (or defects on the surface) mostly occurred at the start of the die radius, where a 0.50 GPa contact pressure was applied on the die radius of 7.5° for a long distance, as shown in Figure 11. In the case of the modified die, it was found that the coating layer was completely worn out, and the boundary between the coating layer and the tool material could be observed at the die angle of 59.0°, where a pressure of 1.866 GPa was applied for a long time, as shown in Figure 11. The worn surface of the modified die at the die angle of 59.0° was further observed by OEM. Microscratches were observed at the worn surface, which were parallel to the sliding direction, as shown in Figure 15. It was found that the tool wear in the sheet metal forming process was generally due to abrasive wear. The observed results confirm again that the contact pressure and the sliding distance are the contact parameters that have a significant influence on the tool wear behavior.

![Figure 14](image2.png)

**Figure 14.** The tool wear surface for the conventional and modified dies observed by OEM.

The wear depths for the conventional die and the modified die were quantitatively measured to estimate the wear behaviors of the respective tool surfaces. The tool wear behavior was evaluated by analyzing the relationship between the measured wear depth and the contact condition of the respective tool surface. The tool wear depth was measured using Leitz Infinity 12.10.6 (Hexagon AB, Stockholm, Sweden), which is a contact-type three-dimensional measuring instrument capable of recognizing relative coordinates with a precision of 0.3 + L/1000 [µm] (L = mm). First, the relative coordinates were recognized in the area where the tool wear did not occur. Next, the wear depth was measured by the absolute difference of the surface profile at the wear occurrence position before and after the wear test. As shown in Figure 16a, the relative coordinate was recognized at the blue dashed line where there was no contact with the blank. Subsequently, the origin of the coordinate was generated. Based on the origin of the coordinate, the tool surface profile was recognized by measuring the solid red line, which is the centerline of the tool, in contact with the blank during the drawing process. As shown in Figure 16b, the point data were measured along with the profile of the tool surface and each point was connected using the spline option in AUTOCAD 2020 (Autodesk, Inc., San-Rafael, CA, USA). The maximum wear depth of the conventional die was 2.25 µm at a die angle of 17°. For the modified die, the wear depth drastically increased up to 10.42 µm because of the high contact pressure. The wear location also moved to the die angle at approximately 59°. From this result, the drawing wear test condition was established successfully to induce the high contact pressure predicted by the numerical simulation.

![Figure 15](image3.png)

**Figure 15.** Abrasive wear of the modified die at the die angle of 59.0° observed by OEM.
Figure 16. Measuring method of the tool wear depth on the die radius: (a) scanning location and (b) surface profile.

4.3. Validation of the Tool Wear Prediction Procedure

The validation process was performed to verify the reliability of the tool wear prediction model and its identified parameters. The experimental and predicted wear depth profiles were compared to evaluate the accuracy of the tool wear prediction procedure. The sliding distance and the contact pressure were investigated to predict the wear depth using the prediction model. The numerical simulation method can be used for investigating the sliding distance and the contact pressure along the die radius. Figure 17a shows the sliding distance with respect to the die radius angle. The decrease in the sliding distance was caused by the sequential onset of the contact between the die and the blank as the punch stroke went upward. Figure 17b shows the contact pressure–sliding distance curves for the two die designs and die angles. By applying the contact pressure–sliding distance histories to the tool wear prediction model, a continuous wear depth profile can be obtained, as shown in Figure 18. For the conventional and modified dies, the maximum wear depths by the prediction model were 2.56 and 10.88 μm, respectively. For the conventional die, the predicted value showed a difference of 0.31 μm from the experimental value, which is an error of 13.78%. For the modified die, the difference between the predicted value and the experimental value was 0.46 μm, i.e., an error of 4.41%. The locations of the maximum wear depth were similar between the experimental and predicted profiles. For comparison, the commonly used Archard wear model was used to predict the wear behavior of the drawing wear tests. For the conventional and modified tools, the maximum predicted wear depths were 13.01 and 8.48 μm, respectively, as shown in Figure 18. Then, the prediction errors of the maximum wear depth were 478.22 and 18.62%, respectively. In the case of the conventional die, the predicted wear depth at a die angle of 7.5° by the Archard
model was significantly over-predicted compared to that of the power law prediction model. This is because the predicted die angle of 7.5° has a relatively long sliding distance (Figure 17b) and the Archard wear model is directly proportional to the sliding distance, while the exponent term for the sliding distance is 0.0573 (<1.0) in the proposed power law model. For the modified tool die, the predicted wear depth at the die angle of 59.0° by the Archard model was quite under-predicted compared to that of the power law prediction model. This is attributed to the high contact pressure at the die angle of 59.0° (Figure 17b). The Archard wear model has a linear relationship with the contact pressure, whereas the proposed model is a nonlinear function with an exponent of 1.7570 (>1.0) for the contact pressure. Therefore, the Archard wear model is proven to have a limitation in predicting the nonlinear behavior of wear in the sheet forming process of DP980 steel. On the other hand, the power-law-type wear model provides more reliable results than the linear model for predicting the wear behavior of DP980 sheets under realistic sheet forming processes.

![Figure 17](image1.png)

**Figure 17.** Contact behavior over the die radius: (a) sliding distance on the die radius and (b) contact history.

![Figure 18](image2.png)

**Figure 18.** Comparison of wear depth profiles obtained by experiment and prediction: (a) conventional die and (b) modified die.

5. Conclusions

This study proposes a prediction method for abrasive tool wear behavior in the drawing process using a DP980 steel sheet by identifying the relationship between the wear depth and the contact conditions on the tool surface.

1. The contact conditions applied to the die surface were evaluated by the sheet metal forming of the B-pillar based on FE simulation. The contact pressure 1.852 GPa
was concentrated at the die corner radius where the actual wear occurred. It was conformed that the contact pressure has a significant influence on the tool wear, by comparing the wear status of the B-pillar die and simulation results.

(2) The pin-on-disk test was conducted for the quantitative evaluation of the wear behavior. Based on the contact pressure of 1.852 GPa of the B-pillar simulation result, the range of test conditions was established. According to statistical analyses using the S/N ratio and the ANOVA result, it was found that contact pressure and sliding distance had a significant influence on the tool wear of the drawing process but the effect of the sliding velocity was minor.

(3) The tool wear prediction model was constructed by the power-law-type regression model to predict the nonlinear evolution of the tool wear depth as a function of the contact pressure and the sliding distance based on the pin-on-disk test results. The U-draw bending test was employed to verify the reliability of the wear prediction model. The modified die was newly designed to accelerate the wear behaviors of the tool surface, which generated a contact pressure four times higher than that of the conventional die. The drawing wear test was conducted using conventional and accelerated drawing tools to measure the wear depth under different contact conditions. For the conventional die and the modified die, the predicted values showed an error of 13.78 and 4.41%, respectively, compared with the experimental values. From the validation process, it can be concluded that the power-law-type wear prediction model could provide reliable prediction for the continuous wear depth profile of the DP980 material and the PVD CrN-coated tool.

(4) The suggested prediction procedure can be further generalized to obtain tool wear predictions by constructing an experimental database of the pin-on-disk tests of combinations of various sheet materials and tool coatings. It has the advantage of saving time and cost because it can predict the tool wear in the drawing process by using pin-on-disk test results. This prediction procedure will help reduce maintenance costs and productivity.

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Nomenclature

\( k, \varepsilon_0, n \) Coefficients of Swift hardening equation
\( a \) Radius of the contact surface (mm)
\( R \) Radius of the elastic sphere (mm)


\[ \begin{align*}
    d & \quad \text{Indented depth (mm)} \\
    E_r & \quad \text{Reduced elastic modulus (MPa)} \\
    E & \quad \text{Elastic modulus (MPa)} \\
    \nu & \quad \text{Poisson’s ratio} \\
    p & \quad \text{Contact pressure acting on the elastic body (MPa)} \\
    p_0 & \quad \text{Maximum contact pressure acting on the elastic body (MPa)} \\
    r & \quad \text{Distance from the center of the circle at the contact area (mm)} \\
    F & \quad \text{Normal force (N)} \\
    V & \quad \text{Sliding velocity (rpm)} \\
    L & \quad \text{Sliding distance (rev.)} \\
    A_p & \quad \text{Tool wear area (mm}^2) \\
    d_w & \quad \text{Wear scar diameter (mm)} \\
    r_p & \quad \text{Pin end radius (mm)} \\
    h & \quad \text{Tool wear depth (µm)} \\
    V_{\text{loss}} & \quad \text{Pin volume loss (mm}^3) \\
    \eta & \quad \text{Signal-to-noise (S/N) ratio} \\
    K, \alpha, \beta & \quad \text{Coefficient of the wear depth prediction model}
\end{align*} \]

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