Evaluation of Sliding Wear Behaviour for STD11 Coated with TiCN Using the Pin-on-Disk Test

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Abstract. The forming process using ultra high strength steel (UHSS) may cause early damage than the expected lifetime of the tool surface due to the high reaction force of the material compared to the conventional steel sheet. This leads to the increase in the cost of maintenance of the tool and the decrease in the product productivity and quality. In this study, the sliding wear behavior of the titanium carbonitride (TiCN) physical vapor deposition (PVD) coated pin against UHSS was quantitatively evaluated from the pin-on-disk test based on the Taguchi method. S/N ratio and ANOVA are used to evaluate the sensitivity of process parameters affecting on the pin wear depth. Finally, a wear prediction model for the TiCN coated pin against UHSS was constructed by the power law equation.

1. Introduction

The demand for the weight reduction has been continuously increasing in the automotive industry over recent years. As a result, the proportion of UHSS(Ultra High Strength Steel) in an auto-body tends to increase, which also could satisfy the strengthened regulations regarding carbon emission and passenger safety [1-2].

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 tool surface during the cold stamping process [3-5]. These defects lead to numerous problems in the surface quality, geometric accuracy, maintenance cost, and productivity. To overcome these problems, special surface coatings should be applied to the tool surface to improve wear resistance. However, this may increase the overall manufacturing cost of the product.

To improve productivity and tool maintenance, the process management based on the accurate prediction of tool wear is required. To achieve the accurate tool wear prediction, it is necessary to obtain the experimental wear database and analyze the wear behavior for tools specially coated for the wear resistance enhancement. The aim of this study is to analyze the wear behavior quantitatively that occurs between the UHSS sheet and the tool for the stamping die using the Pin-on-disk test. The Pin is manufactured by STD11 tool steel coated with TiCN (Titanium Carbonitride). The disk material is selected as DP980 1.4t which is the most widely-used UHSS sheet in auto-body components. The quantitative wear behavior of the pin was confirmed by measuring the wear depth after the pin-on-disk test. Wear characteristics and behaviors for TiCN coated STD11 were evaluated by analyzing the experimental result for the test set established by the Taguchi method and by performing ANOVA for the sensitivity analysis of process parameters. Finally, the wear prediction model for TiCN coated STD11 tool steel was constructed by power law type equation.
2. Experimental setup for the Pin-on-disk test

2.1. Materials
The material of the pin is STD11 tool steel with the elastic modulus of 210 GPa which is the general property of the steel. To improve the wear resistance and hardness, heat treatment is applied to STD11 tool steel. First, quenching was applied to introduce martensite for hardening the STD11 steel, which were heated up from 600°C, 850°C to 1030°C for 1hr 30min at each temperature. After that, tempering was performed twice for 2hr to reduce brittleness occurring from quenching process. The hardness of the heat-treated STD11 tool steel was measured to be 63.5 HRC, which is higher than the hardness value of 58 HRC specified in KS D 3753 [6].
Pin surfaces were coated with TiCN using the PVD process. The hardness of the TiCN coating is 3000 Hv [7]. DP980 1.4t was selected as the disk material. The mechanical properties of DP980 is presented in Table 1.

Table 1. Mechanical properties of DP980 1.4t.

| Thickness (mm) | YS (MPa) | UTS (MPa) | k (MPa) | ε₀ | ε₀ | 0° | 45° | 90° |
|---------------|----------|-----------|---------|-----|-----|-----|-----|-----|
| 1.4           | 721.60   | 1042.0    | 1499.11 | 0.00108 | 0.107 | 0.956 | 0.996 | 1.098 |

2.2. Test method and configuration
The pin-on-disk test is a representative experimental method to analyze, quantify and compare the wear characteristics for various environmental conditions and process parameters. In this test, the tool wear behaviour was investigated by using the pin-on-disk test. Figure 1 shows the pin-on-disk tester consists of pin, disk and weights. Pin contacts with the metallic disk under the normal force loaded by weights. Wear occurs at the contact surface between the pin and the disk due to the relative rotational movement of the disk. Test instrument is TRIBOMETER of CSM Instrument SA.

![Figure 1. Experimental setup for Pin-on-disk test.](image)

2.3. Test conditions
The most significant factors on the tool wear are the normal force and the sliding distance [8-12]. Therefore, these two factors were selected as the control parameter for the Pin-on-disk test. The test range of the normal force was set up to 10 N. The sliding distance was performed up to 1000 revolutions (94.2 m) in order to cause the sufficient wear occurrence of pin. Because the effect of the rotational velocity on the tool wear is relatively smaller than the normal force and the sliding distance, it was fixed to 100 mm/s for all experimental conditions. Table 2 shows the value of control parameters with three levels.
Table 2. Control parameters and their levels.

| Control parameter | Level 1  | Level 2  | Level 3  |
|-------------------|----------|----------|----------|
| Normal force (F)  | 2 N      | 6 N      | 10 N     |
| Sliding distance (L) | 200 rev. (18.84 m) | 600 rev. (56.52 m) | 1000 rev. (94.20 m) |

2.4. Measurement of pin wear depth

In order to measure the wear depth of pin coated with TiCN, the wear area of pin has to be determined. It was measured by using the optical electron microscope (OEM), as shown in Figure 2. The pin wear depth was derived from the measured wear area using the following equations. The wear scar diameter $d$ was calculated by assuming that the pin wear area measured from OEM is a circle.

$$A_p = \frac{\pi d^2}{4}$$

The pin wear depth $h$ is a function of the wear scar diameter $d$

$$h = r - \left( r^2 - \left( \frac{d}{2} \right)^2 \right)^{\frac{1}{2}}$$

where $r$ is pin end radius [13].

Figure 2. Pin wear area measured by OEM.

3. Experimental results

The Taguchi method developed by Taguchi and Konishi [14] is used to identify the characteristics of process parameters and the sensitivity effect. It is a powerful method that has been widely used in engineering problems because an efficient and systematic approach is possible to evaluate the control parameters. In this study, the experimental design set for the Pin-on-disk test was established based on the Taguchi method. The orthogonal array $L_9(3^2)$ was employed by using three factor levels selected in previous section. Table 3 shows the experimental designs based on the orthogonal array $L_9$ and the measured pin wear depth obtained from the pin-on-disk test.

| Run | Normal force (F) | Sliding distance (L) | Pin wear depth (h) |
|-----|------------------|----------------------|-------------------|
| 1   | 10 N             | 1000 rev. (94.20 m)  | 45.678 $\mu$m     |
| 2   | 10 N             | 600 rev. (56.52 m)   | 37.864 $\mu$m     |
The signal-to-noise ratio (S/N ratio) is defined as the ratio of signal (meaningful input) to noise (meaningless input), which checks how much the response of the pin wear depth varies relative to change of each control parameter. The purpose of this study is to identify the response behavior of the pin wear depth as the each control parameter value increase. Therefore, larger-the-better characteristics were chosen as shown by

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

(3)

where \( n \) is the number of experiments and \( y_i \) is the experimental results in \( i \)th experiment.

The results of S/N ratio is shown in Figure 3. As the normal force and the sliding distance increase, the S/N ratio increases. The mean of SN ratios for two control parameters is large enough to change the pin wear depth sensitively. Therefore, it was confirmed that the two control parameters are significant process parameters for the tool wear in the stamping process of UHSS sheets.

![Main Effects Plot for SN ratios](image)

**Figure 3.** Results of S/N ratio on pin wear depth.

ANOVA is a method for evaluating the statistical significance of control parameters. The significance of the normal force and the sliding distance on the pin wear depth was confirmed by F-value and P-value. F-value evaluates how much the control parameter affects the response. P-value is to check whether the control parameter is significant in response. If the P-value is less than 0.05, it means that the control parameter is significant in the response at the 95% confidence level. The ANOVA results for the wear depth of pin are given in Table 4. F-value of the normal force and the sliding distance is 160.49 and 79.26, respectively. F-value of the normal force is larger than that of the sliding distance, which means that the normal force has a more significant effect on the pin wear depth than the sliding distance in the test range.

|   | Normal Force (N) | Sliding Distance (rev.) | Pin Wear Depth (μm) |
|---|------------------|-------------------------|---------------------|
| 3 | 10               | 200 (18.84)             | 36.00               |
| 4 | 6                | 1000 (94.20)            | 40.69               |
| 5 | 6                | 600 (56.52)             | 35.34               |
| 6 | 6                | 200 (18.84)             | 31.52               |
| 7 | 2                | 1000 (94.20)            | 31.44               |
| 8 | 2                | 600 (56.52)             | 26.64               |
| 9 | 2                | 200 (18.84)             | 23.76               |
Table 4. Results of ANOVA for the wear depth of pin.

| Variance source   | Degree of freedom (DOF) | Adjusted sum of squares (Adj. SS) | Adjusted mean squares (Adj. MS) | F-value | P-value |
|-------------------|-------------------------|----------------------------------|---------------------------------|---------|---------|
| Normal force (F)  | 2                       | 247.296                          | 123.648                         | 160.49  | 0.000   |
| Sliding distance (L) | 2                     | 122.125                          | 61.062                          | 79.26   | 0.001   |
| Error             | 4                       | 3.082                            | 0.770                           | -       | -       |
| Total             | 8                       | 372.502                          | -                               | -       | -       |

4. Wear prediction model

The wear prediction model of TiCN coated STD11 tool steel was constructed by using the pin-on-disk test results for the orthogonal array established by the Taguchi method. The wear depth is a function of the normal force and the sliding distance, and it is formulated by the power law type equation as follows:

\[ h = 12.94 F^{0.2342} L^{1.1523} \mu m \]  

(4)

where \( h \) is pin wear depth, and \( F \) and \( L \) are the normal force and sliding distance, respectively. Figure 4 shows the regression result of the formulated wear prediction model. The \( R^2 \) and \( Adj.R^2 \) values of the wear prediction model are found to be 94.58% and 92.77%, respectively. These values support that the power law type regression equation can predict the reliable wear amount of the TiCN coated STD11 tool steel for the stamping process of UHSS sheets. The wear prediction model can be used when designing the tools of the drawing process of actual auto-body parts.

Figure 4. Regression curve fitted by experimental results.

5. Conclusion

This paper identifies the correlation between pin wear depth and control parameters (normal force and sliding distance) by the sensitivity analysis and proposes the wear prediction model for TiCN coated STD11 tool steel. The pin-on-disk test was performed based on the Taguchi method in order to evaluate and quantify the wear behavior according to the normal force and the sliding distance. The statistical analysis by the S/N ratio and ANOVA was found that the normal force and the sliding distance have a significant influence on the wear behavior of the TiCN coated STD11 tool steel. The power law type regression model was constructed to predict the pin wear by using experimental results of pin-on-disk test. It can be effectively utilized to predict the wear amount of TiCN coated STD11 tools in the stamping process of UHSS sheets.

6. References

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