Evaluation of Wear Characteristics for Coating on SKD11 Substrate with Advanced High Strength Steel

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ABSTRACT: Recently Ultra High Strength Steel sheet (UHSS) has been adopted in automotive stamping industry to reduce the weight and enhance the safety of automobile. However, the application of the UHSS sheet faced some difficulty such as die wear and related problems due to high contact pressure on the die surface during the stamping process. In this study, wear tests of pin-on-disc (POD) type were performed to evaluate wear characteristics for the UHSS sheets under dry and lubricated conditions. For five kinds of coatings (TiCN, CrN, TiAlCrN, TiN and TD) on the SKD11 substrate and the uncoated substrates, wear resistances of those die materials under relatively contact sliding with three UHSS sheets was evaluated by the wear characteristics; the wear mass loss, the curve between the coefficient of friction , sliding distance, and galling initiation distance. Among those coatings, the CrN coating shows the best anti-wear performances, respectively.

KEY WORDS: Materials, Advanced High Strength Steel, coating layer, galling initiation, pin-on-disc test, wear characteristics [D3]

1. Introduction

With an increasing need of lightweight material and strong material in vehicles for the purpose of reduction of CO2 greenhouse gas and assurance of crash safety, advanced or ultra high strength steel (AHSS or UHSS, hereafter) is actively and continuously adopted in autobody panels and structural applications. However, there are many problems encountered in stamping operations of AHSS/UHSS sheets such as fracture or springback due to their increased strength and low ductility etc (1, 2).

Moreover, die wear in tribological terminology during stamping / blanking operations is also critical issue because excessive die wear and galling deterioration the quality of stamped part and surface geometry accuracy or cost performance due to frequent replacement of the expensive die sets.

To cope with the die wear matter in mass production of auto parts the die material, AISI D2 (known as SKD11), used for various cold sheet forming application, are conventionally modified with a hardened surface layer using heat treatment or coating process in order to reduce the friction between coating fairs, increase the impact resistance and thus lower the shear forces that leads to wear at the critical area.

Another attempt is to add forming lubricant between the contact surfaces of stamping tool and sheet material or to choose adequate die material having anti-wear resistance property e.g. tungsten cemented carbide, Uddeholm Vancorn 40 and advanced SKD11- based die material like SLD-MAGIC™ (3, 4).

It is known that the contact pressure levels between the sheet blank and punch / die corner radius are very high in order 1.2×σYS ~2.6×σYS (yield strength) for the case of cold stamping operation of the UHSS sheet such as high-manganese austenitic Twinning Induced Plasticity (TWIP) steel, Complex Phase (CP) steel and Mart steel having giga (pascal) tensile strength (5). The TWIP steel is similar to the TRIP steel except that the transformation that occurs during plastic straining is twinning rather than a phase change. The CP steels have extremely fine microstructures of ferrite, bainite, martensite, and precipitation hardening phases. The representative mechanical properties for the TWIP steel are 450MPa (Yield strength), 1000MPa (tensile strength) and 50~54% (total elongation) and The CP steel has 1000MPa, 1200MPa, and 8~10%, respectively (6).

As the application of UHSS sheet increases the stamping engineers are pushed to find a sustainable and robust tool material with high wear resistance (anti-wear property) and low life cycle cost during its usage (7, 8). This is our motivation for this study.

The wear resistance of the tool materials is affected directly by many factors e.g. its hardness, surface interaction with contacting material, normal pressure, physical and mechanical properties of the tool material etc (9).

There are various kinds of die wear test methods; standard methods such as ball-on-disc test method / pin-on-disc test method (ASTM G99-95a) (10) and in-house tribometers developed for different applications and wear conditions such as SRV (reciprocating friction and wear) (4), strip drawing under bending (10), U-bending test (11), CNC-based die wear test (6, 12), robot-based die wear test (13) and slider-on-flat-surface (SOFS) test (14), etc.

Most of these die wear tests have evaluated the wear mechanism and ranked the wear loss or wear rate for die material and coating if needed under the loading of standard diamond tool in BOD test. However, in the actual stamping processes of the
UHSS sheet, the UHSS sheet gets in contact with the die material at every stamping stroke not the diamond tool. From the fact that the tribological behaviors of die material are strongly dependent on the relative properties of contacting materials; die material and sheet material, it is more reasonable to evaluate the wear characteristic of die material contacting with the sheet material used in real stamping operations.

Compared with the ball-on-disc test, the Pin-on-Disc Test (POD test) where the die material with spherical ended pin is in contact with the counter face disc (UHSS sheet materials) during the entire testing duration is well fitted for our purpose to evaluate the wear characteristic between coating material and sheet material. This paper investigates the effect of different coatings such as TiCN, TiAlCrN, CrN, TiN and TD coating deposited on the SKD11 steel on wear characteristic of tool steels which are relatively sliding with three UHSS sheets – TWIP980, TWIP980GI (GI means zinc coated steel) and CP1180 – by using the pin-on-disc test. Two contact conditions of dry and oil lubricated slidings are considered for each test. The wear characteristics of the coated pins are measured in term of wear loss, coefficient of friction (CoF), sliding distance curve, and galling initiation distance.

2. Experiment procedures

POD test has been widely used to identify the wear characteristics of die materials owing to its easiness of testing process as well as its simplification of results computation. In this study, the POD test following the standard ASTM G99-95a (reapproved 2000) is applied and the scheme of wear test machine is presented in Fig. 1, where the pin of die material rotates and the disc of the sheet material is fixed. In this standard test, a spherical ended pin of die material is used for the wear test. The pin runs against a flat disc of sheet material.

To clarify the effect of the coating property on the die wear resistance, three kinds of coating on the pin of die material SKD11 (substrate) are considered such as physical vapor deposition (PVD), chemical vapor deposition (CVD), and thermal diffusion (TD). TiAlCrN, TiCN and CrN are coated by using PVD process, TiN by CVD process, and VC by TD process. Furthermore, the wear test results are also compared with that of uncoated pins.

2.1. Properties of coating layers

To prepare the substrate material for coating, firstly, all the pins, after being cut from a solid of SKD11, were hardened by three levels of temperature 600°C, 850°C, and 1030°C during 60 minutes for each level. Since the quality of the coating layer is strongly influenced on the initial surface preparation of the substrate, heated specimens were polished until reaching a roughness of 0.02μm as recommended from Ref. (15). Finally, all polished pins were used for coating process following the standard of each coating method. More detail information about coating process can be found in Ref. (16, 17).

Observation of the coating layer were carried out on the surface of the pins by the scanning electron microscope (SEM). To see the cross-section view of the coating layer, the magnification of SEM pictures are about 3000x. Additionally, a series of micro hardness tests were performed to measure the hardness of coated layer by using a Ultra Micro Vickers Hardness Testing Machine having Berkovich type indenter. Data of coating thickness, surface roughness and hardness of coating layer for tested pins are summarized in Fig. 2 and Table 1.

![Fig. 1 Schematic view of wear test and dimension of the coated pin](image1)

![Fig. 2 Cross section SEM images of tested specimens including 5 different coatings](image2)

| Table 1 | Properties of coating layers and UHSS sheets |
|---|---|---|---|---|
| Coating | Process type | Coating thickness [μm] | Hardness [HMT] | Roughness Ra [μm] |
| TiCN | PVD | 1.8 | 2487.0 | 0.029 |
| TiAlCrN | PVD | 1.9 | 2256.0 | 0.030 |
| CrN | PVD | 7.9 | 2234.1 | 0.044 |
| TiN | CVD | 2.2 | 1970.4 | 0.024 |
| VC | TD | 6.1 | 2073.5 | 0.026 |
| SKD11 – uncoated | - | - | 813.5 | 0.020 |
| TWIP980 | - | - | 322.3 | 1.07 |
| TWIP980GI | - | - | 73.8 | 1.79 |
| CP1180 | - | - | 698.0 | 0.91 |
According to Table 1, it is clear that the hardnesses of coated pins are significantly high in the range of 2000HMT–2500HMT which is more than twice higher than that of the uncoated pin (substrate SKD11). Additionally, the hardness difference of coated pins is negligible, except TiN (CVD) and VC (TD) coatings which show about 2000HMT hardness.

From the Fig. 2, applying the coating on the substrate material of SKD11 increases the surface roughness of the coating layer. However, these increasing amount are paltry when comparing the roughness of uncoated pins (0.020 μm, Ra) and that of coated pins (maximum 0.044 μm). Besides, it is observed that when the thickness of coating layer is increasing, the roughness of surface is also increasing. The highest roughness was obtained for CrN(PVD) coating of which coating thickness is 7.9 micrometer.

2.2. Pin-on-Disc test

In order to perform the pin-on-disc tests using 5 kinds of coated pins and SKD11 pin, discs with a diameter of 70mm were cut out of plates of three UHSS sheets; TWIP980, galvanized TWIP980GI, and CP1180 sheets. The goal of this work is to clarify the tribological properties of the coated layer in which coated pin shows the best performance of wear resistance for the disc sheets of UHSS materials in pin-on-disc test

In POD test, the disc is raised by air pressure; thence, a compressive load is applied to the end of the pin with radius of 3mm. When the load reaches the required value of 100N, the pin was rotated along the track radius of 11.5mm at a constant speed of 250 rpm, i.e. 0.3m/s similar to actual press forming speed. At this value of compressive load, the contact stress between the pin and the disc in POD test showed a similar value with that between the die and the blank in stamping process of the UHSS sheet as reported by Kim et al. 49

According to Ref. (3), there are four major wear mechanisms governing the wear behavior of alloy systems: abrasion, surface fatigue, adhesion and tribochemical reaction. Hence, the surface observation on the pin as well as the disc after testing is consequence of a combination of these mechanisms. Otherwise, the lubricating condition contributes to final result of wear behavior. However, a full discussion on all of these aspects is a complex job and it is out of the scope of this study.

To identify the effect of the wear characteristics of the coated pins, wear tests for each pair of pin and disc were performed at room temperature with dry condition and oil lubricated condition. In this study, the wear resistances of the coated pins are measured in term of wear loss, galling initiation distance in the CoF, and sliding distance curve according to ASTM G99-95a.

The gall initiation distance is defined as the distance in the CoF curve where the CoF value reaches to the theoretical value of 0.577, i.e., the value for shear yielding and thus sticking occurrence.

\[
\mu = \frac{F}{N} = \frac{T/r}{N} \tag{1}
\]

In the POD test, the torque T acting on the pin was measured under the constant normal load N and the friction force F was used for evaluation of the CoF in Eq. (1). In this study, the value of 0.5 in the CoF curve is conveniently considered as a critical value because in most of the POD tests, a sudden increase in the CoF curve was observed due to severe sticking occurrence.

The lubricant with viscosity of 2.79g/cm·s is smeared on the disc surface before the POD test and the POD test was performed up to 1km sliding distance which is considered to be enough to identify the effect of coating layers on wear resistance.

| Weight loss of pins after POD tests |
|------------------------------------|

| Coating         | TWIP980 | TWIP980GI | CP1180 |
|-----------------|---------|-----------|--------|
| Weight loss(㎎)  |         |           |        |
| Non-lub.        | -0.533  | 0.300     | 0.366  |
| Lab.            | 0.367   | 0.300     | 0.333  |
| Non-lub.        | 0.400   | 0.200     | 0.333  |
| Lub.            | 0.367   | 0.333     | 0.333  |
| Non-lub.        | 0.367   | 0.333     | 0.333  |
| Lub.            | 0.333   | 0.333     | 0.333  |

Fig. 3 Microscopic view of the top of pins after POD test measured as indicated in Fig.1

The weight of each pin with precision of 1 x 10⁻⁴ g was measured five times before and after the POD tests and the wear loss of the pin evaluated by the weight difference was calculated by its averaged value after ignoring the highest and the lowest values.
Prior to weight measurement, the pins was cleaned ultrasonically with 100% acetone for 3 min.

3. Results and discussions

Fig. 3 shows the microscopic views of the POD tested pins contacting with TWIP980GI sheet for dry sliding condition and PCT1180 sheet for lubricated sliding condition. It is clear that large wear damages are shown in the case of TWIP980GI pins for all coatings under dry sliding condition but almost no wear damages appear in the case of CP1180 pins under lubricated sliding condition except TD coating.

Table 2 presents the measured weight loss of the tested pins in the cases of dry and lubricated sliding conditions for different UHSS sheets. As discussed in Ref. (18) for austenitic TWIP steel where both wear rate and CoF are higher under dry sliding condition at the lower sliding rate, higher weight losses are observed in dry sliding condition for all UHSS sheets.

However, when using lubricant on the contact surface, the weight loss of the pin was reduced significantly than the dry sliding

| TWIP980 | TWIP980GI | CP1180 |
|---------|-----------|--------|
| TiCN_hab. | TiCN_hab. | TiCN_hab. |
| TiAlCN_hab. | TiAlCN_hab. | TiAlCN_hab. |
| CrN_hab. | CrN_hab. | CrN_hab. |
| TiN_hab. | TiN_hab. | TiN_hab. |
| TD_hab. | TD_hab. | TD_hab. |
| SKD11_hab. | SKD11_hab. | SKD11_hab. |

Fig. 4 Coefficient of friction and sliding distance curve
condition in most cases of study here. In the case of TWIP980, the weight loss increases in the order CrN<TiN<TiCN<TiAlCN<TiAlCrN.<TD

Also for the case of TWIP980GI, it follows the order of CrN<TiCN<TiAlCN<TiAlCrN<TD. For lubricated sliding of TWIP980GI pins contacting with SKD11 disc the weight loss is moderately less than other coating pins except CrN because zinc material from the disc sheet TWIP980GI transfers and adheres to the pin SKD11.

Moreover, in the case of the CP1180 sheet, weight loss in all cases of tested pin is very small and almost nearly zero. From these experimental results it is recommended that fully lubricating condition should apply to reduce the weight loss of the die during stamping process of the UHSS sheets.

Fig. 4 shows the CoF for all tested pins contacting with the UHSS sheets as a function of sliding distance in the case of lubricated sliding condition. The POD tested results for the case of dry sliding condition have showed very large CoF at the beginning of the tests for all coated pins due to sticking friction and thus galling occurrence and here the results were omitted because most stamping factories add lubricant to prevent die damages in stamping of UHSS sheets.

In the cases of TWIP980 and TWIP980GI sheets, two opposite trends are shown in the curves of CoF and sliding distance. The first trend were seen in the cases of the SKD11 pin. In these cases, the CoF increases dramatically to the maximum value of about 0.52 then it remains at this value up to an abruptly decrease to a value of 0.1 at a certain sliding distance. This phenomenon can be interpreted as at early stage of POD test, the abrasion occurs on the surfaces of contact region due to the low value of surface hardness of the pin.

During experiment, the pin surface was hardened by the plastic deformation under normal compressive load and friction sliding on this surface. Hence, micro surface hardness of the pin increased gradually until a value that is large enough to yield the abrasion on the surface of the pin, which reduced the value of CoF.

For the cases of coated pin (TiCN, TiAlCN, TiN and TD coatings) except CrN coating, experimental data shows a low value of CoF (about 0.1) at early stages of the sliding distance of 200m~400m. After some sliding distance, the value of CoF increases steadily or drastically up to the maximum value of about 0.5 and it largely vibrates with keeping the value until end of the POD test. This severe vibration of the curve after galling initiation can be interpreted as follows; after a severe wear by galling of the material, the material stucked and removed cyclically.

In the case of CrN coated pin, we could not find any galling phenomenon in the curve of CoF and sliding distance and also the CoF keeps a constant value of low level, about 0.1, even though the sliding distance reaches to 1000m.

In the case of CP1180 sheet, all of coated pin except TD coated indicated low CoF of about 0.1. Only the CoF of TD coated pin is over 0.52 at the sliding distance of about 850m. Fig. 5 shows a comparison of the galling initiation distances obtained from all combinations of the pin and disc used in this study. In this figure the upward arrow means there is no galling occurrence until the POD test ends. The galling initiation distance was defined as the distance where the CoF value in the coefficient of friction and sliding distance curve reaches to the value of 0.52. From this figure, it is seen that the galling mostly does not happen when using the CP1180 disc. It is thought that hardness of CP1180 is much higher than other discs as indicated in Table 1. This high hardness may explain why galling does not happen for CP1180, or not.

In the case of other sheet material of disc, the best result was achieved when using the CrN (PVC) coated pin, at which the POD tests were stopped without any observation of galling. More details, by judging the rank of wear resistance from the galling initiation distance we concluded that the wear resistance increases in the order of SKD11<TiAlCrN<TiC<TiN<TD for TWIP980 sheet and SKD11<TiCN<TiAlCrN<TiN<TD<CrN for TWIP980GI sheet.

4. Conclusions

In this paper, POD tests for five kinds of coated pins, and uncoated pin contacting three kinds of UHSS disc have been performed. The wear characteristics of the tested pins were evaluated in terms of wear loss, the coefficient of friction, sliding distance curve, and galling initiation distance. Also the influence of lubricant on POD test was investigated. The results are summarized as follow:

1) Surface roughness and the thickness of the coating layer are in correlation together. When the thickness of the coating layer is higher, the surface roughness of the pin is high, and vice versa. Different coating method and different deposition yield different value of thickness of coating layer as well as surface roughness. However, the micro surface hardness of all coated pins is similar. It is seen that coating method has strongly influenced the thickness of coating layer than the hardness of that.

2) When evaluating wear resistance of coating layer using non-lubricant POD test, it is difficult to evaluate the weight loss of the thin coating layer and the steel sheet because the severe sticking phenomenon occurs at the early stage of sliding distance in POD test. Therefore, to evaluate wear resistance with weight loss needs to find other evaluating method.

3) Result of POD tests showed two opposite trend of evaluation of CoF when using uncoated and coated pins. The micro surface hardness of the pin has a strong effect on the measurement results of CoF. By identifying the galling initiation distance during experiment, effect of coating layer on the wear characteristics was revealed. It is concluded that the CrN (PVD) coating among the coatings on SKD11 substrate considered in this study improved significantly the wear resistance of the pin.

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References

(1) The Automotive CO2 Emission Challenge, http://www.adlittle.com/downloads/tt_adlreports/ADL_AMG_2014_Automotive_CO2_Emissions_Challenge.pdf, (Access Date August. 01. 2015)
(2) Advanced High Strength Steel Application Guidelines, Version 5.0, edited by S. Keeler, March 2014, www.autosteel.org (Access Date August. 01. 2015.)
(3) ASM Metal Handbook, Vol.5: Surface Engineering, 2nd Printing. ASM, International, Materials park, Ohio, 1996
(4) J. Hardell, High temperature tribology of high strength boron steel and tool steels, Licentiate Thesis, Lulea University of technology, Lulea, Sweden, June, 2007
(5) Tooling solutions for advanced high strength steels, http://www.uddeholm.com/files/Tooling_solutions.pdf, (Access Date February. 06. 2016)
(6) Y.S. Kim, K.C. Park, J.B. Nam, B.H. Lee, Die materials and their wear evaluation for press forming of high strength steels, Trans. Mater. Proc. Vol. 24, No. 2, pp.138-146 (in Korean) (2015)
(7)E. Billur, Die materials and wear in stamping AHSS, STAMPING Journal® Magazine (2010)
(8) Y.S. Kim, J.J. Kim, Evaluation of die wear in stamping of giga strength steel sheet, Internal report of POSCO project, Incheon, Korea, 2015.
(9) ASTM G99-95a, 2000, Standard Test Method for Wear Testing with a Pin-on-Disc Apparatus
(10) B. Boher, D. Attaf, L. Penazzi, C. Levaillant, Wear behavior on the radius portion of a die in deep drawing: Identification, localization and evolution of the surface damage, Wear, Vol. 259, No. 7-12, pp.1097-1108 (2005)
(11) S. Nishino, T. Hirao, E. Togashi, K. Ohya, K. Yokose, K. Toishi, A. Nakao, Y. Komine, Siding damage evaluation of coating for press forming dies, JSAE Annual Congress Proceedings, (in Japanese) No.21-08, 20085220, pp.13-16 (2008)
(12) O. N. Cora, Development of rapid die wear test method for assessment of die life and performance in stamping of advanced/ultra high strength steel (A/UHSS) sheet material, Ph.D thesis, Virginia Commonwealth University, Richmond, Virginia, November, 2009
(13) O.N. Cora, N. Namiki, M. Koc, Wear performance assessment of alternative stamping die material utilizing a novel test system, Wear, Vol. 267, No. 5-8, pp. 1123-1129 (2009)
(14) F.W. Lindvall, On tool steel, surface preparation, contact geometry and wear in sheet metal forming, Ph.D thesis, Karlstad University, Karlstad, Sweden, 2011
(15) Y. J Jeon, S. H. Kim, K. T. Yoon, Y. M. Heo and T. G. Lee: Indirect Prediction of Surface Damage for a Press Die with Wear Characteristics and Finite Element Stamping Analysis, Korean Society for Technology of Plasticity, Vol. 23, No. 1, pp. 29-34 (2014)
(16) T. G. Lee: A study on the dimensional change of STD11 die material in heat treatment and the optimum work condition of PVD die coating, MS Thesis, Kyungpook National University, 2007
(17) E. Adoberg, V. Podgurski, P. Peetsalu, L. Lind, V. Mikli, P. Hvizdos and P. Kulu: The effect of surface pre-treatment and coating post-treatment to the properties of TiN coatings, Estonian Journal of Engineering, Vol. 18, No. 3, pp. 185-192 (2012)
(18) I. Mejia, A. Bedolla-Jacuinde, J.R. Pablo, Sliding wear behavior of a high-Mn austenitic twinning induced plasticity (TWIP) steel microalloyed with Nb, Wear, Vol. 301, pp. 590-597 (2013)