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Short communication

Wear performance assessment of alternative stamping die materials utilizing a novel test system

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ABSTRACT

Stamping of Ultra/Advanced High Strength Steel (U/AHSS) sheets leads to high contact stresses and non-uniform strains. These, in turn, cause high wear rates and springback. In order to prevent the excessive wear effect in stamping dies, various countermeasures have been proposed such as alternative coatings, modified surface enhancements in addition to the use of newer die materials including cast, cold work tool, and powder metallurgical tool steels.

A new slider type of test system was developed to replicate the actual stamping conditions including the contact pressure state, sliding velocity level and continuous and fresh contact pairs (blank-die surfaces). A vertical machining centre, with vertical and normal force sensors mounted on its spindle, was employed to generate the contact pressure and controlled movement of die samples on sheet blank. Several alternative die materials in coated or uncoated conditions were tested against different AHSS and stainless steel blanks under certain load, sliding velocity, lubrication circumstances. This paper briefly describes the test system and experimental methodology, and presents the results for wear resistance performance of an air-hardening cold-work tool steel sample with different coatings tested against DP 600 AHSS grade sheet blanks.

1. Introduction

Die wear is an undesired and unpredictable failure and downtime reason in metal forming operations. It directly affects the part formability and surface quality, and causes production loss, cost increase and delays. AISI D2 die material has been a widely used tool steel for various forming applications in the stamping industry. However, it is found to be not suitable for stamping of Advanced High Strength Steel (AHSS) grades (DP, TRIP, etc.) because of excessive wear/galling and toughness issues. Several attempts have been sought to find alternative solutions for die wear issues including development of different die materials, coatings, and surface enhancements.

The literature is abundant in terms of various die wear test methods developed for different applications and wear conditions. However, they either do not reflect the actual stamping conditions or require special, cumbersome and costly preparations that are not applicable in small spaces such as laboratory environment. For example, in pin-on-disk test [1,2], the die material (in form of a very small pin) is in contact with the same disc surface (sheet metal of interest) during the entire testing duration, which is not a true representation of the actual stamping operation conditions, because at every stamping stroke the die material gets in contact with new sheet metal surfaces (i.e., virgin surface conditions). In addition, as opposed to the actual stamping conditions, the contact surface area is very small in the pin-on-disk wear tests.

SRV (Schwingung Reibung Verschleiβ: reciprocationg friction and wear) tester is one of several configurations of pin-on-disk test systems, and same surfaces of die and sheet materials of interest are in contact during the whole test [3,4]. Similarly, the twist-compression test (TCT) [5,6] is based on the repeated contact tracks on the same sheet material surface, and it is found to be suitable for comparing the test variables (such as lubricant) rather than obtaining an absolute measure of wear [7]. Likewise in load-scanner test, a stationary test cylinder is used as a tool sample, and it is in contact with another rotating cylinder which is the sheet material of interest [8]. In this test, the same contact surface is scanned repeatedly in every cycle; however, in a real stamping operation a die/punch is in contact with fresh, untouched blank surfaces.

On the other hand, other wear tests such as (a) strip pulling [9,10], (b) u-bending/deep drawing [11–13], (c) strip drawing [12,14,15], (e) draw bead [16], (f) combined draw-bead and strip pulling [17], and (g) bending under tension or radial strip drawing [12,18] are more representative of the actual stamping conditions; however, they are lengthy (e.g. ~15–70 km strip length is needed in combined draw-bead and strip pulling test), costly and require

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special arrangements such as specially slit coils, large test area and extra equipment like hydraulic clamps, presses, coilers/de-coilers, etc.

With an increasing need to introduce new lightweight materials into the auto body and structures, newer and alternative die materials, coatings, surface treatment/enhancements, and lubricants become necessary to ensure prolonged die life, competitive part cost and consistent high part quality. Accurate and rapid testing of all possible combinations of die material, coating and surface treatment using the existing wear testing methods is not feasible in terms of time, cost and reliability.

The main motivation in this study was to establish a test system that provides reliable results, in a rapid manner and also to simulate/control the parameters as much as possible to real conditions. The test system we proposed eliminates the repeated contact surface issues by continuous sweeping of fresh/untouched blank surface by means of tool/die sample.

This paper, in essence, presents the results of a study for which the aim was to investigate the effect of different coatings applied on recently introduced air-hardening cold-work tool steel, containing 1% carbon, 8% chromium, 2% molybdenum and remainder of iron, on die wear resistance under stamping conditions of DP 600 AHSS grade sheet blanks. The second section of this paper introduces the test system, experimental conditions, die material and sheet blank properties in a detail. Experimental measurements and results are discussed in the third section. The paper is concluded with conclusions and recommended future work.

Nomenclature

k	specific wear rate ($mm^3/(N\,m)$)
F_n	applied normal load (N)
s	sliding distance (m)
V	wear volume (mm^3)

2. Test system

An alternative die wear test system was developed with the premise of rapid and accurate wear performance assessment of alternative die materials for newer stamping materials. Its earlier design and comparison with existing die wear test methods were discussed in other published work of the authors [19], a brief description of the updated test system is as follows: This die wear test system is based on the use of precise and controlled motion of a vertical machining center (HAAS VF-3 CNC)s *x*-, *y*- and *z*-axes and spindle (no rotation). A load sensor was mounted on the spindle through a holder which also houses the die sample of interest. AHSS sheet blanks are laid on the *x*–*y* table with clamps at four corners as can be seen in Fig. 1. CNC was programmed for the precise pressing of die sample and one-way scratching/sweeping on the AHSS sheet blank. Normal force occurring at the die and blank interface was recorded during the tests. Fig. 2 shows the die sample dimension and an actual picture with the wear tracks on the sheet blank.

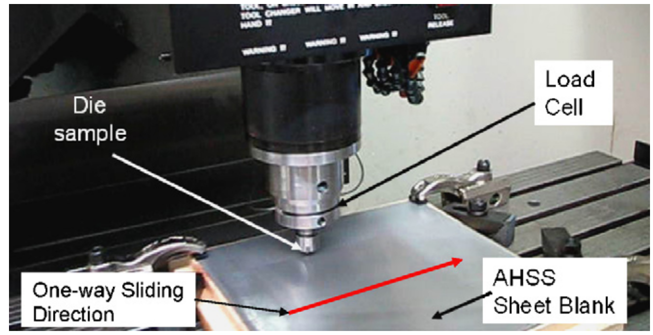

Fig. 1. Test system.

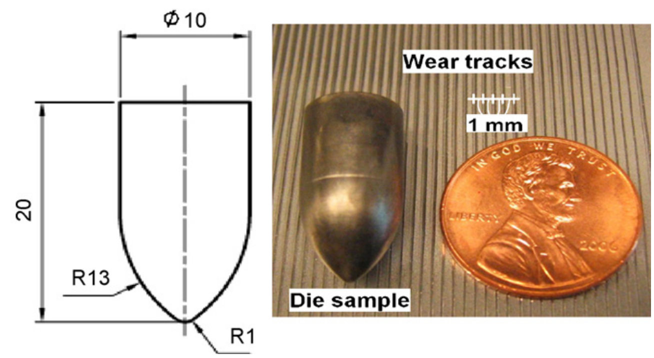

Fig. 2. Die sample dimensions and its actual photo on wear tracks.

Table 3
Die samples tested, hardness values and average surface roughness values (Ra).

Substrate (die sample) + coating configuration	Substrate hardness (HRC)	Average surface roughness, Ra, before test (μm)
I) Substrate + TD coating	60.4	0.025
II) Substrate + radical nitriding TiCN (PVD)	61.0	0.063
III) Substrate + TiCN (PVD)	61.0	0.051
IV) Substrate + multi-layered CVD (TiC + TiCN + TiN)	61.4	0.079

2.1. Experimental procedure and test materials

Each die sample was tested along two (2) km track distance under an average normal load of 200N with a sliding speed of 0.33 m/s utilizing the above mentioned system. For repetition purposes, 3 replications were performed with the Sample (I) given in Table 3. DP 600 (Dual-Phase, 600 MPa ultimate tensile strength) sheet blanks of 330 mm × 330 mm × 1 mm were used in tests. Chemical composition, average surface roughness, and hardness values for the die samples and sheet blanks are tabulated in Tables 1–4.

Table 1
Chemical composition of air-hardening steel substrate material.

Substrate Material	C	Si	Mn	Cr	Mo	V
An air-hardening cold-work tool steel	0.96%	0.91%	0.37%	8.1%	2%	0.26%

Table 2
Typical chemical composition of DP600 steel sheet blanks [20].

Material Grade	Chemical composition					
	C	Mn	Si	Al	S	P
DP 600	0.106	0.800	0.310	0.044	0.005	0.01

Table 4
Hardness and average surface roughness (Ra) values for DP 600 sheet blank.

Hardness measured (HV_1)	Average surface roughness, Ra (μm)
203	0.24

Specimens provided by DAIDO Steel Co. Ltd were prepared with the following procedure: Firstly all the samples are roughly machined before pre-heat treatment. In the heat treatment die samples were exposed to gas quenching at 1030 °C, then tempered for 1 h at 550 °C. After the heat treatment applied; the die samples are machined to final dimensions and polished prior to coating process (Thermal Diffusion: TD, Physical Vapour Deposition: PVD, and Chemical Vapour Deposition: CVD). In particular, the second sample is radically nitrided before its PVD coating. In radical nitriding process, different from conventional nitriding, the coating process is done under NH_3 and H_2 environment and it eliminates the formation of "white layer" which is brittle and needs to be cleaned prior to PVD coating process. The combination of radical nitriding and PVD coating provides increased hardness and peel off resistance for coatings. TD and CVD coated samples are heat treated after coating process again. The final procedure for the sample preparation is polishing of coated samples. Coating thicknesses for all the samples tested are in the range of 5–10 μm as reported by provider.

3. Experimental results and discussion

Performance evaluation of die samples was based on the following measurements (1) mass loss, (2) surface profile (roughness) and (3) microscopic evaluations. In order to have information about surface roughness, contact surface of die samples are measured with a stylus (AMBIOS XP-1, Ambios Tech., CA, USA) which is a contact-type of device. All the measurements are taken normal to the sliding direction which was followed during the test. It has been observed that there is no significant difference between initial and resultant surface roughness values for the die sample contact surfaces given in Tables 3 and 5 respectively. Even, the surface roughness is improved for all the die samples except PVD coated sample. Figs. 3–6 show the micrographs for the resultant contact surfaces and their 3-D topographies obtained by using a HIROX digital microscope KH-7700 (Hirox-USA Inc., NJ, USA) while Figs. 7–10 show SEM pictures of the tested samples at their tips with different magnification levels. Energy dispersive x-ray (EDX) analyses were also performed for tested samples on coating layer. In addition to carbon content, vanadium, which is main ingredient in TD coating, was detected on the coating layer of Sample I while; titanium (Ti) was detected on coating layers of other three samples as expected. Specifically, for the multi-layered CVD coated sample (Sample IV), TiC on the substrate and TiN on the top of coating layers and TiCN between those were detected. From optical microscope and SEM images, It is indisputably obvious that the contact surfaces of the PVD coated (samples II and III) samples underwent considerable changes compared to TD and CVD coated samples. Sliding directions are clearly visible for those samples and adhesion type of wear observed on contact surfaces. From Figs. 3 and 6, it is noticed that the coating is not completely removed from the specimens' contact surface. Specifically, amount of wear debris for the test of TD coated

Table 5
Measured surface roughness values for test samples.

Test material + coating	R_a (μm)	R_{ku} (μm)	R_q (μm)
(I) Substrate + TD Coating	0.018	9.057	0.025
(II) Substrate + Radical nitriding TiCN (PVD)	0.059	6.218	0.080
(III) Substrate + TiCN (PVD)	0.068	5.393	0.092
(IV) Substrate + multi-layered CVD (TiC, TiCN, TiN)	0.053	4.88	0.071

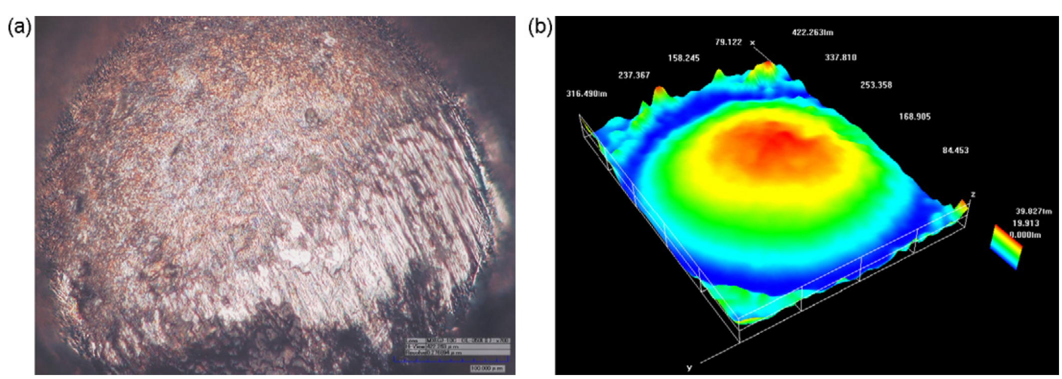

Fig. 3. (a) Micrograph of die sample (I) with TD coating (700×); (b) 3-D topography of the worn surface.

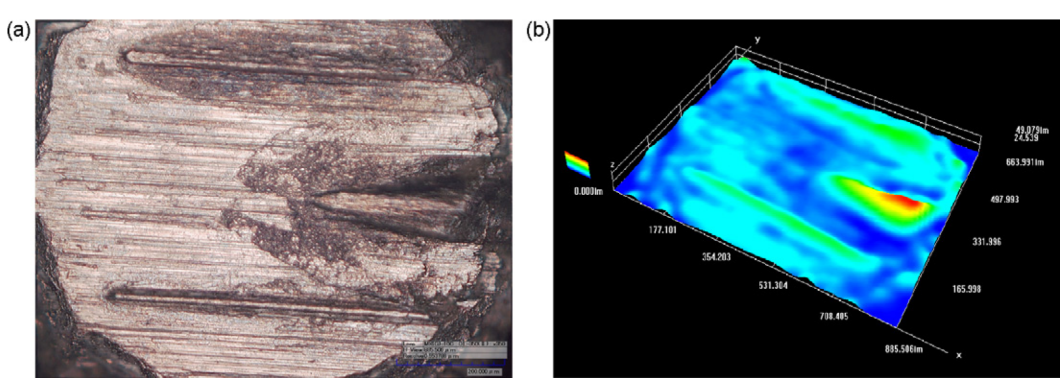

Fig. 4. (a) Micrograph of die sample (II) with radical nitriding + TiCN (PVD) coating (350×)); (b) 3-D topography of the worn surface.

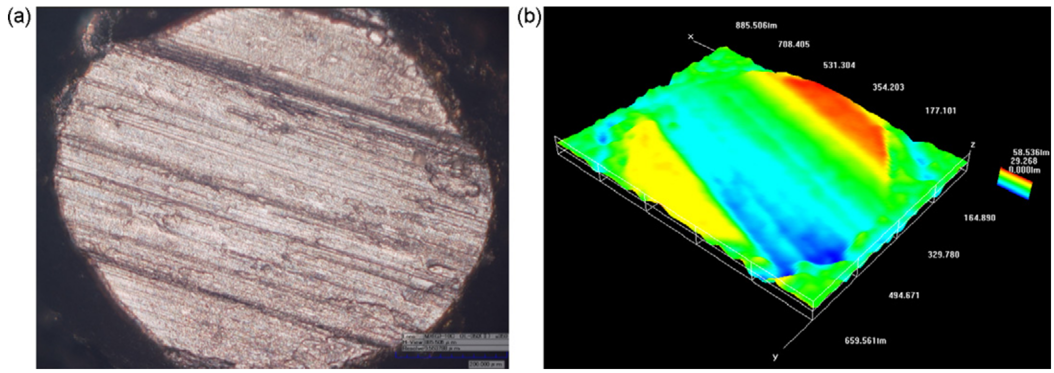

Fig. 5. (a) Micrograph of die sample (III) with TiCN (PVD) coating (350X)); (b) 3-D topography of the worn surface.

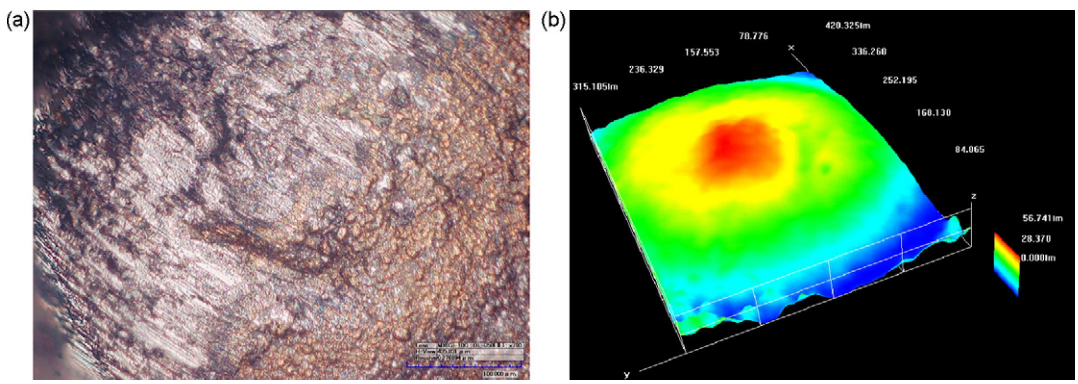

Fig. 6. (a) Micrograph of die sample (IV) with multi-layered CVD (TiC, TiCN, TiN) coating (700×); (b) 3-D topography of the worn surface.

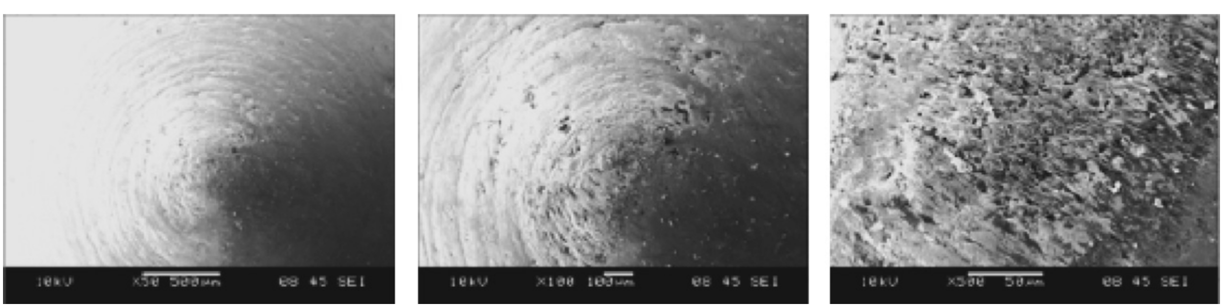

Fig. 7. SEM picture of die sample (I) with TD coating at the tip (magnifications: (a) 50×, (b) 100×, (c) 500×).

sample was higher than any other sample; although the mass loss of that sample was the least among the test samples. It is concluded that the durable and tough TD coating produced more wear debris on the sheet blank compared to the other samples coated with different techniques. These facts have been verified with the specific wear rate measurements. Specific wear rate (k) was used to asses the wear resistance performance. It is defined as follows:

$$k = \frac{V}{sF_n} \quad (1)$$

where V is wear volume, s stands for sliding distance, F_n is applied normal load, and k is for specific wear rate ($mm^3/(N\,m)$). Wear vol-

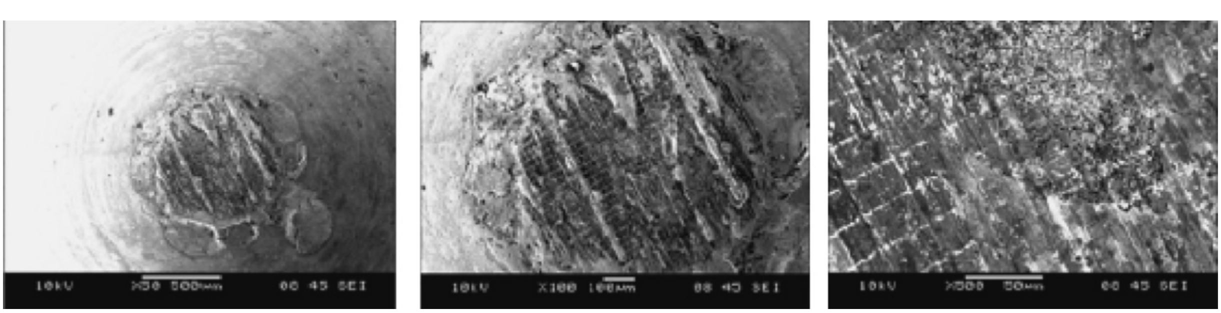

Fig. 8. SEM picture at the tip of die sample (II) with radical nitriding + TiCN (PVD) coating (magnifications: (a) 50X, (b) 100×, (c) 500×).

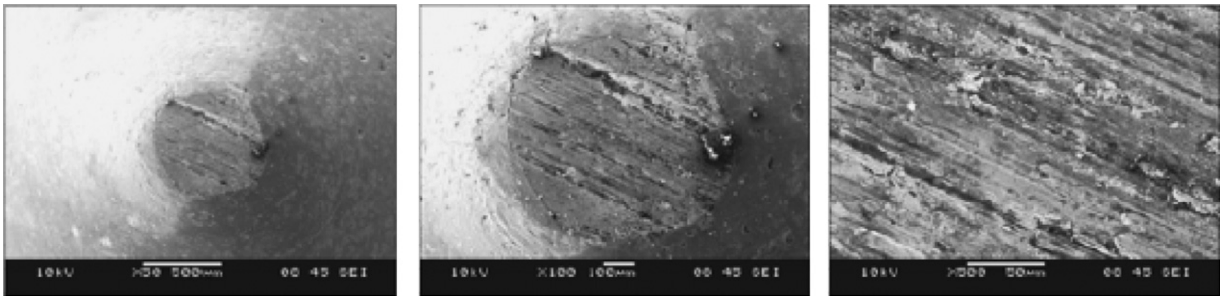

Fig. 9. SEM picture at the tip of die sample (III) with TiCN (PVD) coating (magnifications: (a) 50×, (b) 100×, (c) 500×).

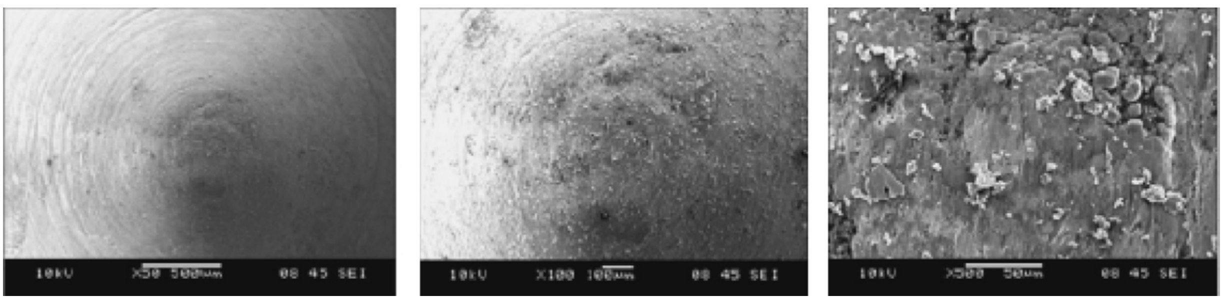

Fig. 10. SEM picture at the tip of die sample (IV) with multi-layered CVD (TiC, TiCN, TiN) coating (magnifications: (a) 50×, (b) 100×, (c) 500×).

ume measurement is based on the values of measured mass loss and density of the substrate and coating material. For the specimens (samples I and IV), in which the wear is only on the coating, the coating densities were included in calculations. For the other specimens (samples II and III) both coating and substrate material densities were taken into account in calculating specific wear rate values. Density of the substrate material was reported as 7870 kg/m^3 by sample provider. Other coating density values are obtained from the literature [21,22]. Sliding distance is 2 km and average normal load is 200N as mentioned above. Tabulated results and bar chart form for specific wear rates of the test samples are given in Table 6 and Fig. 12 respectively. The smaller value stands for higher wear resistance. Fig. 11 shows Vickers type of micro-hardness measurements for the coated samples starting from coating surface to inner substrate.

As reported from the previous studies [23,24] and experienced in this study, radical nitriding process resulted in higher coating hardness value when the Samples (II) and (III) are examined. Contrary to expectations, sample (II), with the highest coating hardness, did not perform the best. Die sample (II), coated with radical nitriding and PVD and with a hardness of 61.0 (HRC) on the substrate and 980 (HV) on the coating, performed relatively low compared to other tested samples. Considering the hardness values of the substrate and coatings from Table 3, and Fig. 11, it can be concluded that harder substrate or coating does not give higher wear resistance every time.

It is clearly seen that the performance of the TD and CVD coated samples are very close to each other, and far better than PVD coated samples. As discussed above, these samples were the ones that coating was not removed from the contact surface completely. The drawback for the TD and CVD coating technologies is the limitation of the coating replacement. Typical CVD and TD coatings are applied at temperatures greater than 1800 °F to increase molecular activity within the substrate. During these high temperature coating processes, atomic diffusion occurs from substrate to surface and forms a third compound combining with the coating material. This can produce a hard coating, but the diffusion towards surface is limited. Thus, as tools and coatings wear, the second application of these coatings usually lasts about 70% as long as the first application; a third application generally has a life only 30% that of the original tool. When the diffusion is not feasible anymore, the process ceases to provide any benefits [25].

For repetition purposes, 3 replications were performed with the Sample (I). Based on good results obtained from replications as depicted in Fig. 12, repetitions for other cases were not performed. The coating was not removed from the substrate completely in any replication test, which strengthened the consistency of test results. Although there is no agreed upper limit for specific wear rate to assess the performance of materials, all of the specific wear rate values for the tested materials are well below compared

Table 6
Calculated specific wear rate values for tested samples.

Die material + coating	Specific wear rate ($mm^3/N.m$)
(I) Substrate + TD Coating	4.223×10^{-8}
(II) Substrate + Radical nitriding TiCN (PVD)	1.844×10^{-7}
(III) Substrate + TiCN (PVD)	1.099×10^{-7}
(IV) Substrate + multi-layered CVD (TiC, TiCN, TiN)	4.353×10^{-8}

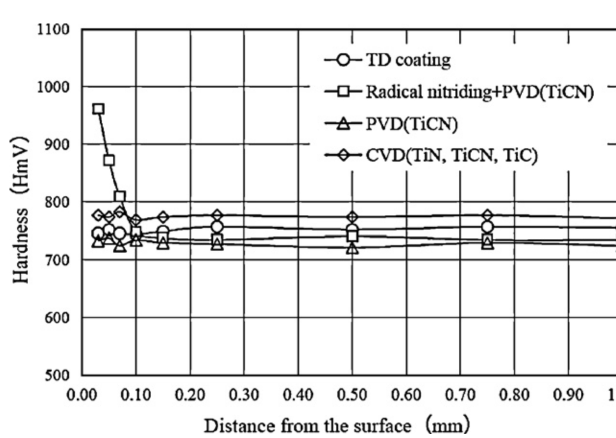

Fig. 11. Micro-hardness values for the tested samples from coating surface to inner substrate.

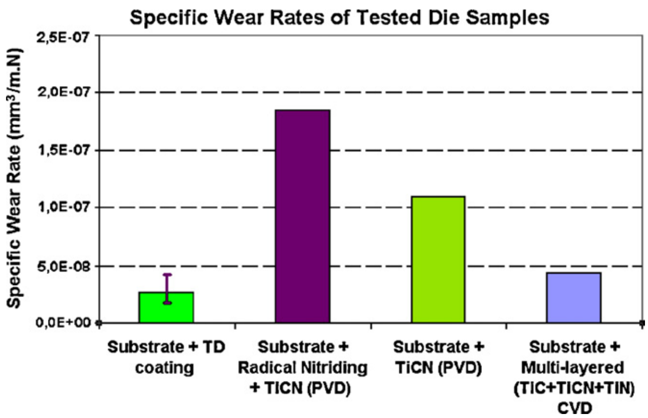

Fig. 12. Specific wear rates for tested samples.

to 1×10^{-6} mm^3/(m N) which is regarded as limit value by some researchers [26].

In literature, several researchers investigated the effect of coating applications on wear. In their work, Weist et al. studied the effect of various coatings including nitrided layers, hard chromium plating as well as PVD, CVD or ion implantation on tool wear. They noted that the best results were obtained for PVD and TD coated punches in a quest for reduction of wear in bulk metal forming processes [27]. In another study by Dubar et. al., the performance of cold forging tool coated with PVD and CVD coatings was examined and the findings showed that the better friction and lifetime results were obtained by CVD coated tools [28]. As can be understood from these studies and several others, there is no best coating technique that can handle all conditions. The best choice requires finding the optimum combination of substrate and coating material which vary with operation variables.

4. Conclusion and future work

The effect of coating technique on die wear resistance has been investigated for air-hardening tool steel against advanced high strength steel sheet blanks of DP 600 using a new die wear test system that enables better mimicking the stamping operations conditions compared to conventional friction/wear test systems. The proposed test system enables fast, cost-effective, reliable wear resistance assessment especially for the die materials used in forming of advanced high strength steel sheet blanks.

Test results showed that the TD and CVD coatings have performed better in terms of mass loss and consequently specific wear rate without significant coating removal from the contact surface. The other significant outcome from the study is the fact that, the harder substrate and/or coating does not provide the best performance conditions as experienced with sample (II) in this study. There are several components that contribute to have high wear resistant products, and these components vary with the test/manufacturing variables such as contact pressure, sliding velocity, temperature, lubrication conditions etc. The compatibility of the substrate material and the coating applied is crucial for antiwear properties as well as the formation of strong bond between substrate and coating material. Higher coating hardness values may contribute less peel-off resistance due to brittleness effect. Although the stated coating thickness range for the samples is very tight, the uncontrollable coating thickness differences may also contribute to the performance of the tested samples. Based on these reasons, tested samples need further metallurgical investigation to find out the effect of hardness values of coating and substrates.

The studies aimed to investigate the effect of substrate hardness on wear resistance made in previous publication of authors [29]. The future studies will include the effect of the different substrate materials coated with same technique, effect of different lubrication, performance assessment of different lubricants.

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