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A study of DLC coatings for ironing of stainless steel

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Abstract. Stamping of sheet metal components without lubrication or using minimum amount of hazard free lubricant is a possible solution to diminish health hazards to personnel and environmental impact and to reduce production costs. This paper studies the application of diamond-like coating (DLC) under severe lubrication conditions by adopting strip reduction testing to replicate industrial ironing production of deep drawn, stainless steel cans. Three DLC coatings are investigated; multi-layer, double layer and single layer. Experiments revealed that the double layer coating worked successful, i.e. with no sign of galling using no lubrication even at elevated tool temperature, while the other two coatings peeled off and resulted in severe galling unless lubrication was applied.

1. Introduction

In tribologically severe stamping operations e.g. ironing and punching of stainless steel the phenomenon of galling, i.e. breakdown of the lubricant film followed by pick-up of workpiece material on the tool surface and scoring of subsequent workpiece surfaces may appear if lubrication is inadequate. Mineral oils containing EP additives are therefore commonly applied to avoid galling in sheet stamping production. Application of these lubricants requires additional costs for pre-cleaning, lubrication as well as post-cleaning after stamping. Applying lubricants such as chlorinated paraffin oils to avoid galling furthermore poses risks to personnel health and working environment. Insufficient post-cleaning promotes hazardous chemical residues on the sheet surface, which may be unacceptable in cases like biomedical and food container products.

A promising way to eliminate these hazardous lubrication issues is to perform the sheet stamping under dry friction condition by applying hard coatings to the tools, which impedes pick-up. A few promising tool coatings have been reported to work in sheet stamping under dry friction conditions or with minimum lubrication of aluminium, stainless steel and titanium. They include Diamond-like Coatings (DLC) [1], [2] and pure diamond coating [3]. Both coating types are able to produce thousands of sheet components without galling. In addition, a diamond coated die resulted in a 20% reduction of the drawing force in dry deep drawing with a subsequent 10% ironing of magnesium alloy at elevated temperature as compared to lubrication with MoS₂ [4]. Drawbacks of the pure diamond coating are cost and the fact that it can only be deposited on specific tool materials, e.g. tungsten carbide. Furthermore, it leaves a rough surface of crystalline diamond, which needs to be polished by a special ultrasonic technique to obtain a smooth surface. Adopting DLC, literature reports the necessity of lubrication in sheet stamping at high normal pressures such as ironing or blanking [5] due to the generation of a high shear stress in the DLC coating resulting in peeling off of the coating from the tool surface.

Tailoring the interaction between the coating and the tool surface can enhance adhesion and promote longer coating life. For instance, multilayer coating structures [6] segregate multi coating films with improved internal stresses of each coating layer, while retaining high hardness, good adhesion and wear
The multi coating layers serves to improve hardness and modulus of elasticity of a coating structure, which increases the load-carrying capacity due to improved mechanical properties of the coated tool surface. Adopting an increased surface roughness of the tool substrate prior to coating [8] is a useful technique for improved coating adhesion but it generates a larger surface roughness after coating, which is difficult to polish to a sufficiently low final surface roughness.

The present study is concentrating on intermediate coating layer structures, while retaining the DLC as the top coating layer. The tribologically severe strip reduction test, which emulates industrial ironing of stainless steel sheets, is suitable to examine promising coating candidates for severe forming conditions and is therefore used in this study.

2. Test Setup

Figure 1 shows the schematic of the strip reduction test [9] and the Ø15 mm tool pin with and without DLC coating. A drawing speed \( v = 65 \text{ mm/s} \) and a thickness reduction \( r = 15\text{–}25\% \) were applied with three different types of DLC coated tools and a non-coated tool surface as a reference. The workpiece material was austenitic stainless steel EN1.4307 (AISI 304L), 1.2 mm thick, 15 mm wide and 500 mm long. It was used in the “as-received” condition with a surface roughness \( Ra = 1.4 \text{ µm} \). The stress-strain curve of the workpiece material was determined by uniaxial tensile testing, which gave the following according to the Swift’s flow curve expression: \( \sigma_0 = C (B + \varepsilon)^n = 1830 (0.091 + \varepsilon)^{0.58} \text{ MPa} \).

![Tool pin with no coating](image1)

![Tool pin with DLC coating](image2)

Figure 1. Schematics of strip reduction emulates ironing [9].

3. Test materials and coating types

The tool material was a PM cold work tool steel, UHB Vanadis 4, with high carbon and chromium content and alloyed with manganese, molybdenum, silicon and vanadium. The tools were through-hardened and tempered to 62 HRC and subsequently polished to \( Ra = 0.02 \text{ µm} \) before coating. Three DLC coating structures were evaluated; single layer, double layer and multi-layer coatings as described in Figure 2. The roughness after coating was the same as before \( Ra = 0.02 \text{ µm} \).

![Figure 2](image3)

Figure 2. The three coating structures: Type A, Type B and Type C.

Two severe lubrication conditions were chosen. One was lubrication with a low viscous, plain mineral oil without additives as listed in Table 1, and the other one was reduction with no lubricant.

| Oil type         | Product name | Kinematic viscosity \( \eta @ 40 \text{ °C} \) |
|------------------|--------------|---------------------------------------------|
| Pure mineral oil | CR5-Sun 60\(^a\) | 60                                          |

\(^a\) 50 wt % mixture of Houghton Plunger CR5 (\( \eta = 660 \text{ cSt} \)) and Sunoco Sun 60 (\( \eta = 10 \text{ cSt} \))
4. Experimental Procedure
The experiment started by cleaning the tool and workpiece surfaces from any remnants of pick-up, oil and other contaminants. In case of lubricated experiments, lubricant was subsequently applied to the workpiece surfaces, after which reduction was carried out with 300 mm drawing length. In some of the experiments, the tool was pre-heated to either 80°C or 110°C, using a thermal cartridge heater inserted in the upper tool loading the tool pin, see Figure 1. During the experiments, the load and temperature were recorded and saved in a custom made LabView program. After the experiment, the tool surfaces were scanned in a light optical microscope (LOM) and the workpiece surface roughness was measured across the strip for every 30 mm drawing length by a tactile roughness profilometer, Taylor Hobson Form TalySurf.

5. Application to Strip Reduction test
5.1. Screening test of DLC coatings
A preliminary screening test was performed at 15% reduction in order to examine the performance of the DLC coatings. During the experiments, the tools were either kept at room temperature of 20°C or heated up to 80°C. Figure 3 shows the average drawing loads using a tool with or without DLC coating at different lubrication conditions. Low load was observed with the DLC type B in all test conditions. Testing of all other tools without lubrication led to larger drawing loads. Low drawing loads were obtained when testing the tools with the CR5-Sun60 oil except for the non-coated tool at elevated tool temperature.

![Figure 3. Average drawing loads at different tool and lubrication conditions.](image)

Figure 4 shows measurement of final workpiece roughness for all test conditions. The DLC coatings A and B works satisfactorily when applying a thin layer of pure mineral oil, CR5-Sun 60, for tools at room temperature as well as elevated temperatures, see Figure 4a and Figure 4b. Increased roughness was found when applying the DLC type C and the uncoated tool. Large surface roughness indicates that the tool surface experienced severe pick-up. For the case of dry friction, the DLC type B was the only one that could withstand the severe test conditions at room temperature as well as elevated temperature, as indicated by the low surface roughness, see Figure 4c and Figure 4d. The other two DLC coatings and the uncoated tool resulted in heavy scoring as seen by the large sheet roughness and in some cases the strip broke after a short drawing length.

It was furthermore clear that the DLC type B showed the best adhesion to the tool substrate as seen on the LOM images in Figure 5. The other tools suffered peeling off of the DLC coating and pick-up of workpiece material on the tool surface. Table 2 summarizes that the DLC type B is superior in all test and lubrication conditions, and that the other DLC coatings can only function with the presence of a thin oil film.
Figure 4. Sheet roughness versus drawing length with tool surface as parameter: a) CR5-Sun60 at 20°C, b) CR5-Sun60 at 80°C, c) Dry at 20°C, and d) Dry at 80°C.

Figure 5. Images of workpiece and tool surface conditions after screening experiments under dry lubrication at a tool temperature of 80°C.

Table 2. Overall performance on the tool with and without DLC coatings (Rating: 1-Excellent, 2-Good, 3-Satisfactory, 4-Poor).

| Lubrication condition | Tool temperature | No coating | Coating types |
|-----------------------|------------------|------------|---------------|
| CR5-Sun 60            | 20 °C            | 4          | 2 1 3         |
| CR5-Sun 60            | 80 °C            | 4          | 2 1 3         |
| Dry                   | 20 °C            | 4          | 4 1 4         |
| Dry                   | 80 °C            | 4          | 4 1 4         |
5.2. Severe testing of DLC coating type B

Two more severe experimental test series at 15% and 25% reduction with a tool temperature of 110°C were carried out on coating type B. Figure 6a shows an expected increase of the drawing load with increased reduction, whereas the surface roughness in both cases was lower than the initial one, see Figure 6b. Adopting the double layer coating film by depositing a metallic coating layer like Hyperlox® in between the DLC film and the tool substrate can therefore improve adhesion strength in the DLC film and even perform well under the extreme test conditions in sheet stamping of stainless steel at elevated tool temperature. The present results are in good agreement with findings in literature [10] using a scratch test.

**Figure 6.** a) Drawing load and b) sheet roughness $Ra$ with DLC coating type B under dry condition at different reductions and tool temperature 110°C.

5.3. Repetitive experiments with DLC coating type B

A repetitive experimental test series was performed on the DLC coating type B under dry friction conditions with 15% reduction and a tool temperature of 110°C. The investigation aimed at examining the durability of the coating as regards persistence towards pick-up. Figure 7a shows the drawing loads and the workpiece roughness $Ra$ reaching a stable value after several strokes with no pick-up. This is verified by the workpiece roughness at the last stroke, where workpiece surface roughness $Ra = 0.11 \ \mu m$ was lower than the initial roughness $Ra = 0.14 \ \mu m$, see Figure 7b. The results indicate a good adhesion at the interface between the DLC, Hyperlox® and the tool substrate and a coating that can sustain high, repetitive normal pressure and shear stress.

**Figure 7.** a) Drawing load and b) sheet roughness $Ra$ after testing with the DLC type B coating under dry condition with a reduction of 15% and a tool temperature of 110°C.

6. Simulation of Industrial Production Case

Simulation of an industrial production with ironing stainless steel cups in EN1.4307 was carried out using the Universal Sheet Tribo-Tester (UST2) shown in Figure 8, which can run multiple tests continuously from a coil [11]. The strip reduction test schematically shown in Figure 8 was selected to perform an off-line evaluation of the coating type B. The test parameters were chosen in accordance with the industrial production process: 24% reduction, 50 mm/s drawing speed, idle time between each
stroke of 1.8 s and sliding length 10 mm. The test materials are described in Table 3. The lower tool is the DLC type B coated test tool, which was tested under lubrication and dry conditions, respectively, whereas the upper tool is a dummy tool provided with an AlCrN based coating and lubricated with an environmentally benign mineral oil with additives, see Table 4. Figure 9a shows constant drawing load and stable tool rest temperature even after 1,000 strokes, and no sign of pick-up on the tool surface was observed. This is verified by measurement of sheet roughness $Ra$ shown in Figure 9b, where both sheet surfaces performed under lubricated and dry conditions were lower than the initial roughness. The results has thus shown that the DLC type C is capable of ironing without lubrication of stainless steel, which is otherwise very prone to galling.

**Figure 8.** Schematics of strip reduction emulating ironing in a tribo-tester [11].

**Table 3.** Test materials.

| Components          | Dimension      | Roughness $Ra$ | Surface coating | Surface condition          |
|---------------------|----------------|----------------|-----------------|---------------------------|
| Upper tool          | Ø15×82 mm      | 0.02 µm        | AlCrN           | Hardened and tempered to 62 HRC |
| Lower tool          | Ø15×34 mm      | 0.02 µm        | DLC type B      | Hardened and tempered to 62 HRC |
| Workpiece           | $W \times t = $ | 0.14 µm        | -               | “as-received” condition    |
| (EN1.4307)          | 30×1.0 mm      |                |                 |                           |

**Table 4.** Properties of the test lubricant.

| Oil type             | Product name     | Kinematic viscosity $\eta$ (cSt @ 40°C) |
|----------------------|------------------|----------------------------------------|
| Mineral oil with additives | Rhenus LA 722086 | 800                                    |

**Figure 9.** a) Drawing load and b) sheet roughness $Ra$ after testing with the coating type B under dry friction with test parameters similar to industrial case under dry condition.
7. Conclusion

The present study adopted a strip reduction test for emulating industrial ironing of stainless steel cups to test promising DLC coatings at room temperature as well as elevated tool temperatures. Three DLC types of coating were evaluated; single layer DLC, double layer (DLC/Hyperlox®) and multi-layer (DLC/CrN/Cr). The experiments revealed that the double layer (DLC/Hyperlox®) coating is a promising coating candidate for production without lubrication. It gave a smooth surface finish of the tested strips with no pick-up on the coated tool surface. Intermediate metallic layers like Hyperlox® between the DLC film and the tool substrate ensured good adhesion of the DLC coating and are expected to work effectively under severe conditions in sheet stamping of stainless steel.

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