MYTRIBOS Malaysian Tribology Society
Jurnal Tribologi
Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

# A study of anti-seizure tool coatings of ironing of stainless steel

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KEYWORD

Tool coating
Diamond-Like Carbon
Ironing
Sheet stamping
Lubrication
Friction

ABSTRACT

Sheet stamping of stainless steel with coated tools alone may not necessarily impede galling unless hazardous mineral oils are applied. The present study focuses on an investigation of a double-layer tool coating structure applied in a continuous strip reduction test emulating the conditions in production by ironing. The coating films consists of Diamond-Like Carbon (DLC) and Hyperlox®. The results revealed that the DLC/Hyperlox® coating was functioning effectively without peeling off and galling if nonhazardous lubricant was applied. This has improved the tribological system significantly since the coating allowed the hazardous lubricant to be abandoned. Numerical analysis using a thermo-mechanical analysis supports the experimental findings, where the new tribo-system minimizes the temperature at the tool/workpiece interface by reducing the friction.

## 1.0 INTRODUCTION

The breakdown of lubricant film often leads to galling, and therefore application of the hazardous lubricants has spurred industrial interest in tribologically severe stamping operations, e.g. deep drawing and ironing of stainless steel and aluminium alloys. Application of these hazardous lubricants like chlorinated paraffin oils requires additional costs for pre-cleaning, lubrication as well as post-cleaning after stamping and they furthermore poses risks to personnel health and working environment. Insufficient post-cleaning, furthermore promotes hazardous chemical residues on the sheet surface, which may be unacceptable in cases like biomedical and food beverage can products.

A promising way to eliminate these hazardous lubrication issues is to perform the sheet stamping under dry friction condition or using hazard free lubricant to the hard tool coating,

Received 21 August 2017; received in revised form 29 September 2017; accepted 11 December 2017.
To cite this article: Sulaiman et al. (2018). A study of anti-seizure tool coatings of ironing of stainless steel. Jurnal Tribologi 17, pp.1-14.

which impedes pick-up and galling. A few promising tool coatings have been reported to work in deep drawing of aluminium, stainless steel and titanium under dry friction conditions or with minimum lubrication. They include Diamond-Like Carbon (DLC) coating (Murakawa et al., 1999; Podgornik et al., 2006) and pure diamond coating (Tsuda et al., 2009; Tsuda et al., 2011). Both coating types are able to produce thousands of sheet components without galling. 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 (Kataoka, 2009). Adopting DLC, literature reports the necessity of lubrication in sheet stamping at high normal pressures such as ironing or blanking (Podgorniket al., 2011) due to the generation of a high shear stress in the DLC coating resulting in peeling off of the coating from the tool surface.

Although a thin layer coating deposited on the tool surface can improve frictional and wear properties of the coated tool surface, stresses induced in the coated tool becomes a major problem since they influence the adhesion strength of the coating. Tailoring the interaction between the coating and the tool surface is a method to prevent the adhesion problem. By depositing multilayer coating structures on the tool surface improved internal stresses of each coating layer are obtained, while retaining high hardness, good adhesion and wear properties (Aizawa, et al, 2008; Vetter, 2014). The multilayer coatings with optimised layer thickness serves to improve hardness and modulus of elasticity of the coating structure, which increases the load-carrying capacity of the coated tool surface (Holmberg et al., 1998). Adopting an increased surface roughness of the tool substrate prior to coating (Kataoka, 2008) 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.

A preliminary series of experiments of the three different DLC tool coating structures demonstrated that the new, double-layer coating, namely DLC/Hyperlox®, showed promising results under severe test conditions, i.e. at high thickness reduction and tool temperature, with no sign of galling in ironing of stainless steel without lubrication (Sulaiman et al., 2017). However, a major issue when testing, has been to determine the onset of galling as a function of most important process parameters, i.e. normal pressure, sliding length and tool temperature. These process parameters need to be identical to the production conditions since the new, double-layer DLC coating has not been tested in industrial production at varying tribological conditions. Hence, a long-term experiment of the new DLC coating under conditions similar to industrial production is therefore important to determine the risk of galling.

The present study focuses on the double-layer coating structure in a continuous laboratory tribology test, which simulates production conditions. The tool surfaces are deposited with two different double-layer coatings; DLC/Hyperlox® coating and Hyperlox®/Hyperlox® coating. The tribologically severe strip reduction test, which emulates industrial ironing of stainless steel sheets, is suitable to identify promising coating candidates for severe forming conditions and is therefore used in this study. A numerical simulation, coupling mechanical and thermal analysis, was performed to evaluate the material deformation and heat generation at the tool/workpiece interface.

## 2.0 COATING TYPES

In the present study, investigations were carried out with two double-layer coating structures, namely DLC/Hyperlox® and Hyperlox®/Hyperlox®. Figure 1 and Figure 2 depicts schematically the cross section surface morphologies of the two single-layer coating films, DLC and Hyperlox®, deposited directly to the tool substrates.

The DLC comprises of a gradient amorphous Carbon Hydrogen (aC:H) DLC coating structure supported by two other coating films, CrN and CrCN, which acts as bonding layers. The aC:H DLC coating was chosen because it has a good combination of high wear resistance and low friction to prevent galling (Carlsson, 2005; Podgornik et al., 2004). Meanwhile, the Hyperlox® is a stand-alone, modified TiAlN coating film. The high content of aluminium in the Hyperlox® coating results in high hardness. Previous experience by the company has shown that the very good adhesion of the Hyperlox® coating reduces the wear and thereby increases tool life and productivity (Neergaard, 2017). The thickness of the two coating layers DLC and Hyperlox® was 3 μm.

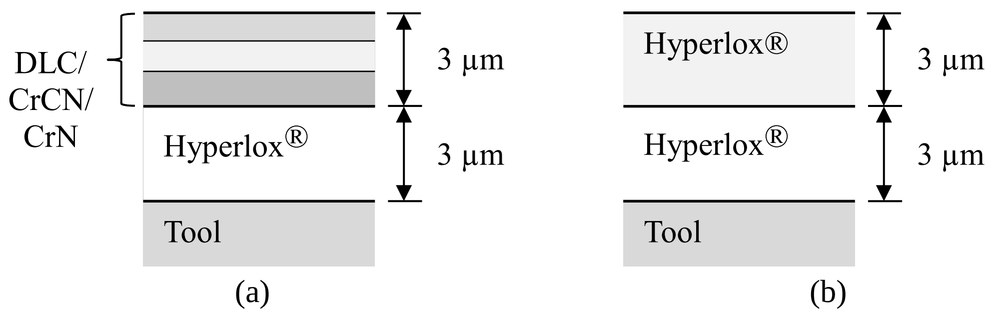
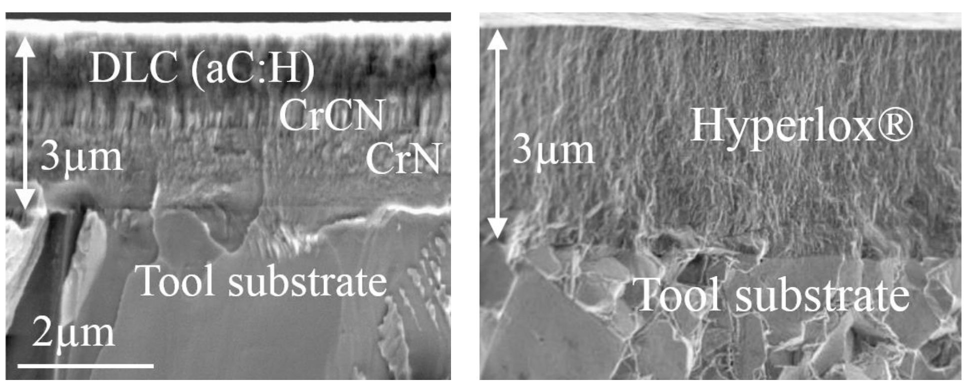



Figure 1: Double-layer coating structures: (a) DLC/Hyperlox® coating and (b) Hyperlox® / Hyperlox® coating.




(a) (b)

Figure 2: Cross sectional surface morphologies of the two single-layer coating films deposited directly to the tool substrates; (a) DLC and (b) Hyperlox® coatings. Images courtesy of CemeCON Scandinavia A/S (Neergaard, 2017).

## 3.0 SCREENING TEST OF TOOL COATINGS

### 3.1 Test setup

At first, the screening experiment was carried out. The purpose of the screening experiment is to identify the capability of the test coatings prior to the next test campaign on the automatic tribo-tester under close control of the tribologically severe test conditions. This is to avoid the need to use money, time or other resources on too many long-term tests.

The screening experiment has been conducted on a manually operated sheet tribo-tester, see Figure 3 (Andreasen et al., 1997). Testing has been performed by drawing the stainless steel strip over a fixed Ø15 mm tool pin while the upper, shoe-formed tool loads the tool pin. The tool pin has been coated with the above mentioned coatings shown in Figure 1. Before coating the tool pins were polished to a surface roughness Ra = 0.02 μm and the roughness was the same after coating. The workpiece material is austenitic stainless steel EN1.4307 (AISI 304L), 1.2 mm thick, 15 mm wide and 500 mm long. It has been used in the "as-received" condition with a sheet surface roughness Ra = 1.4 μm. A drawing speed υ = 65 mm/s and a thickness reduction r = 15% were applied.

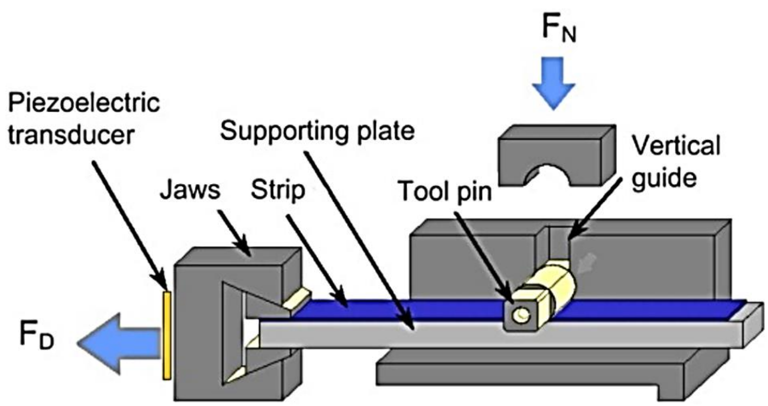



Figure 3: Schematic of strip reduction emulating ironing (Andreasen et al., 1997).

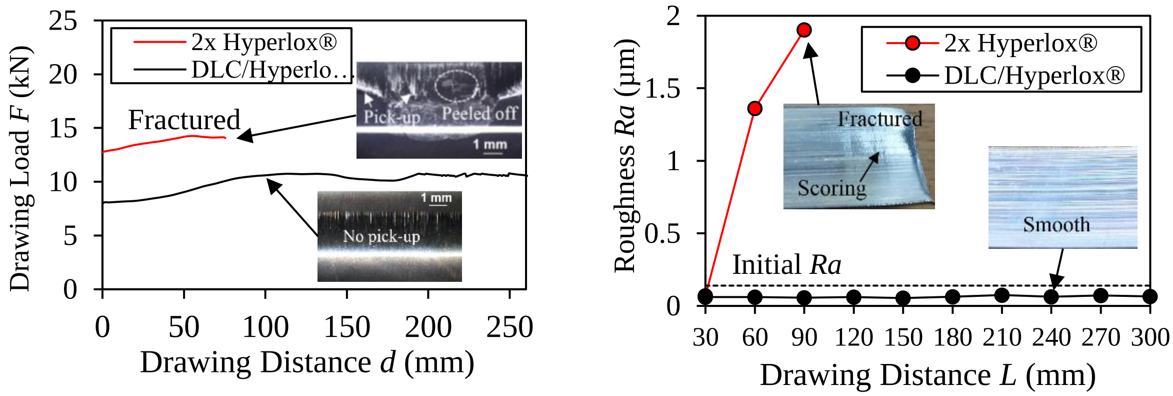
### 3.2 Test procedure

The experiment started by cleaning the tool and workpiece surfaces from any remnants of pick-up, oil and other contaminants. The strip reduction has been carried out with 300 mm drawing length, and with tools preheated to 110°C using a thermal cartridge heater inserted in the upper shoe-formed tool loading the tool pin, see Figure 3. During the experiments, the load and temperature were recorded and saved by 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.

### 3.3 Results and discussion

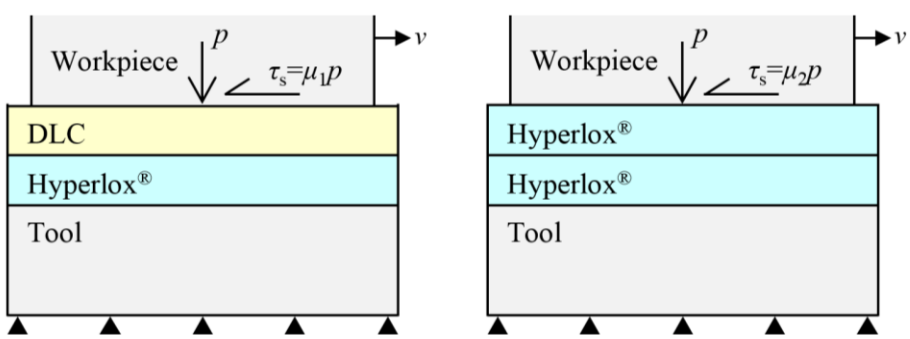
Figure 4(a) shows drawing load as function of drawing distance. A lower drawing load was observed with the DLC/Hyperlox® coating than with to the double-layer Hyperlox® coating and no pick-up on the coated tool surface was observed with the former coating. As regards the double-layer Hyperlox® coating severe pick-up was detected on the tool surface and in some areas, the coating was peeled off. The results were further verified by measurement of the final workpiece roughness seen in Figure 4(b).

A very low surface roughness was achieved by the DLC/Hyperlox® coating, while the Hyperlox®/Hyperlox® coating resulted in heavy scoring on the strip surface and the strip broke after a short drawing length. The results indicate that the Hyperlox® coating offers a good adhesion between the DLC and the tool surface but is unable to act as the anti-seizure coating film that can sustain high shear stresses, see Figure 5. The screening test suggests that the DLC/Hyperlox® coating shall be the only one tested in the following, continuous test campaign.




(a) (b)

Figure 4: (a) Measurement of drawing load and tool surface condition, (b) Measurement of sheet roughness Ra and formed sheet surface condition after drawing the stainless steel under dry lubrication condition.




(a) (b)

Figure 5: Illustration of a good adhesion by (a) the DLC/Hyperlox® coating in comparison to (b) the Hyperlox®/Hyperlox® coating due to the difference in friction at the tool/workpiece interface.

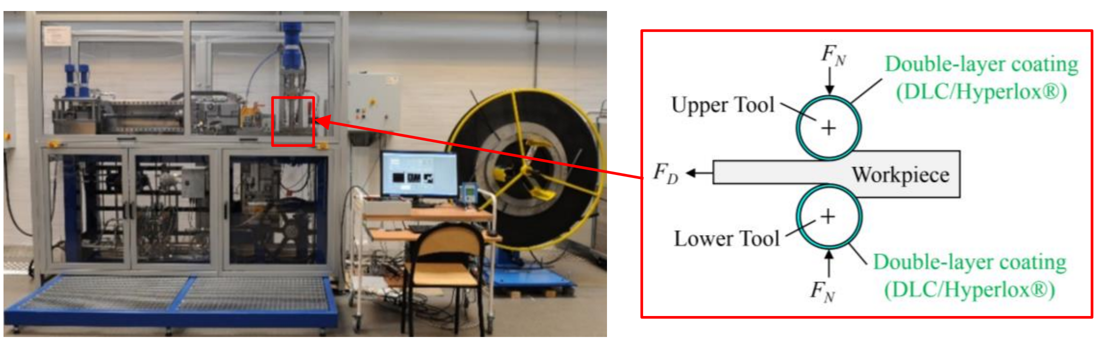
## 4.0 LONG-TERM ANALYSIS OF TOOL COATINGS

A full-scale simulation replicating the ironing stage in a continuous production was carried out to evaluate the DLC/Hyperlox® coating performance after 1,500 strokes, since the collaborating stamping industry partner has experienced that if a tribo-system can function with a threshold of 1500 strokes without galling, it is a promising candidate for full-scale production tests.

### 4.1 Test setup

Laboratory simulation of an industrial production with ironing of stainless steel EN1.4307 cups is carried out using the Universal Sheet Tribo-Tester (UST2) shown in Figure 6a, which can run multiple tests continuously from a coil at pre-set sliding length and sliding speed. The strip reduction test, schematically shown in Figure 6b, was selected to perform an off-line evaluation of the DLC/Hyperlox® coating. The test parameters were chosen in accordance with a specific industrial production process as listed in Table 1.

A round, non-rotating Ø15 mm tool pin, see Figure 6b, is pressed towards the test strip supported by a thicker tool plate. Reduction in thickness can be varied, and it was held at 24% in the present long-term experiments. The strip is subsequently drawn in horizontal direction up to a maximum sliding length 10 mm under constant reduction and constant drawing speed υ = 50 mm/s. Drawing force was measured by a piezoelectric transducer. Threshold sliding before the onset of galling is determined by visual inspection of the drawn strip and by roughness profile measurements of the strip surface perpendicular to the drawing direction with 100 stroke intervals. The experimental setup allows eight experiments with the lower tool pin before changing to another tool pin, by turning the tool 45° after each experiment, whereas, four experiments is possible with the upper tool pin by turning the tool 90° after each experiment.




(a) (b)

Figure 6: (a) Tribo-tester, UST2, and (b) strip reduction emulating ironing.

Table 1: Industrial production process parameters.

| Test parameters | Values |
|---|---|
| Reduction | 24 % |
| Drawing speed | 50 mm/s |
| Idle time between each stroke | 1.8 s |
| Sliding length | 10 mm |

### 4.2 Test materials

The test campaign was performed with a stainless steel EN1.4307 (AISI304L) coil, 1.0 mm thick and 30 mm wide. It was used in the "as-received" condition with a sheet surface roughness Ra = 1.4 μm. The stress–strain curve of the workpiece material was determined by plane strain compression test. The material work hardening shown in Figure 7 follows Voce's model quite well, $\sigma_f = \sigma_o + (\sigma_\infty - \sigma_o)[1-\exp(-n\varepsilon_{eff})]$ MPa = 107 + (1368 − 107)[1-exp(-5.243 $\varepsilon_{eff}$)].

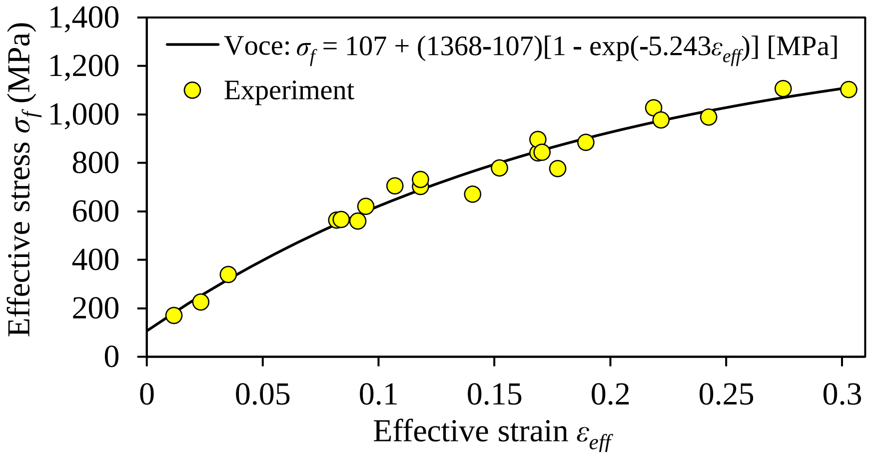



Figure 7: Experimental result and Voce flow curve expression for the stainless steel EN1.4307 sheet.

The tool material was a Powder Metallurgical (PM) cold work tool steel, UHB Vanadis 4, with a 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 μm before coating. The roughness after coating was the same as before Ra = 0.02 μm. The tool material properties are listed in Table 2. The upper and lower tool geometries are shown in Figure 8.

Table 2: Tool materials and specifications.

| **Components** | **Dimension** | **Roughness *Ra*** | **Tool condition** |
|---|---|---|---|
| Upper tool (Vanadis 4) | Ø15×82 mm | 0.02 μm | Hardened and tempered to 62 HRC |
| Lower tool (Vanadis 4) | Ø15×34 mm | 0.02 μm | Hardened and tempered to 62 HRC |

(a) (b)

Figure 8: The Ø15 mm non-rotating a) upper and b) lower tool pins deposited with the double-layer DLC/Hyperlox® coating.

Two lubrication conditions were chosen for the experiments. One of them was a dry friction condition. The other one was lubrication with a hazard free lubricant, a high viscosity plain mineral oil without special additives. The lubricant properties are listed in Table 3.

Table 3: Tool materials and specifications.

| **Oil type** | **Product name** | **Kinematic viscosity $\eta$ (cSt @ 40 °C)** |
|---|---|---|
| Pure mineral oil | CR5 Houghton Plunger | 660 |

## 4.3 Test procedure

Each experiment started by cleaning the tool surfaces from any remnants of pick-up, oil and other contaminants. The experiment was run up to 1,500 strokes. If galling was detected before reaching 1,500 strokes, it was stopped. During the experiment, the maximum drawing load Fmax and tool rest temperature Ti were recorded and saved by 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 100 strokes by a tactile roughness profilometer, Taylor Hobson Form TalySurf.

## 4.4 Results and discussion

A continuous ironing test was performed with the DLC/Hyperlox® coating under tribologically severe test conditions. The experiment aimed at examining the durability of the coating as regards persistence towards pick-up. One of the experiments were performed under dry friction conditions whereas the other one were carried out with lubricated strip. 12.8 g of CR5 lubricant was applied for 1,500 strokes, which covered a nominal contact area of 900,000 mm2. This gives a lubrication amount of 14.2 g/m2.

Figure 9 shows the maximum drawing load Fmax reaching a stable value from the beginning in both experiments with test parameters similar to the industrial case excluding work hardening due to prior deformations in the industrial production. The tool rest temperature Ti kept increasing slowly in both cases as seen in Figure 10. The dry friction test resulted in higher tool rest temperature Ti than the lubricated one. Figure 11 presents the measurement of the sheet roughness Ra after every 100 strokes. No scoring was observed on the workpiece.

In the dry friction test, no pick-up was observed after 1,000 strokes, Figure 12a, but slight peeling off of the DLC coating occurred after 1,500 strokes, see Figure 12b. In the lubricated test, no pick-up was noticed after 1,500 strokes as seen in Figure 12c. The results indicated good adhesion at the interface between the DLC, Hyperlox® and the tool substrate and a coating that can sustain a high, repetitive normal pressure and shear stress. In case of lubrication, monitoring the tool temperature is important since an increase of temperature at the tool/workpiece interface leads to lubricant film breakdown and galling (Bay & Ceron, 2014). These thermal effects are evaluated in the next section.

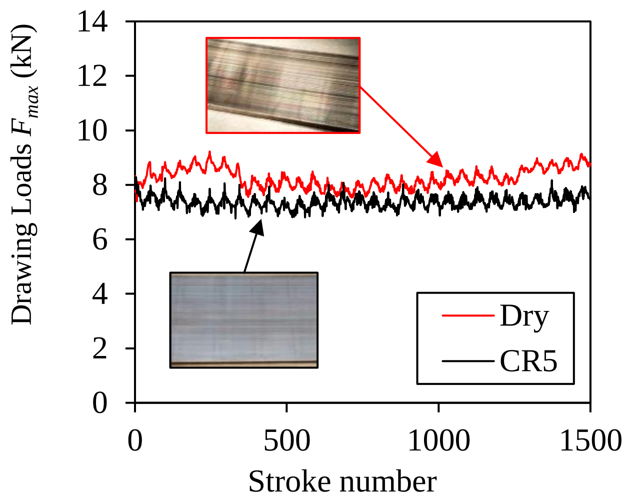



Figure 9: Experimental drawing load and formed sheet surface condition after drawing the stainless steel under dry and lubricated conditions.

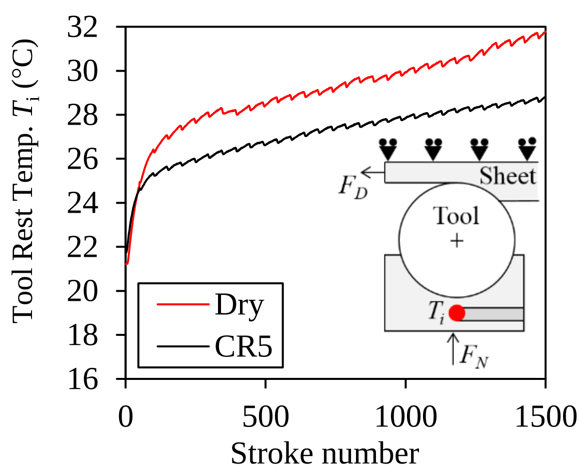



Figure 10: Tool rest temperature and schematic of thermocouple location.

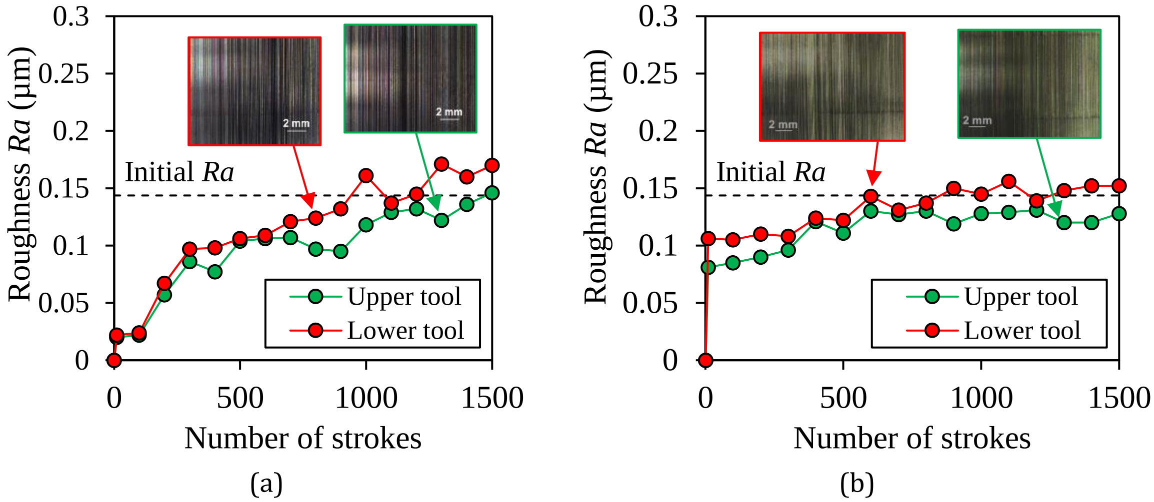
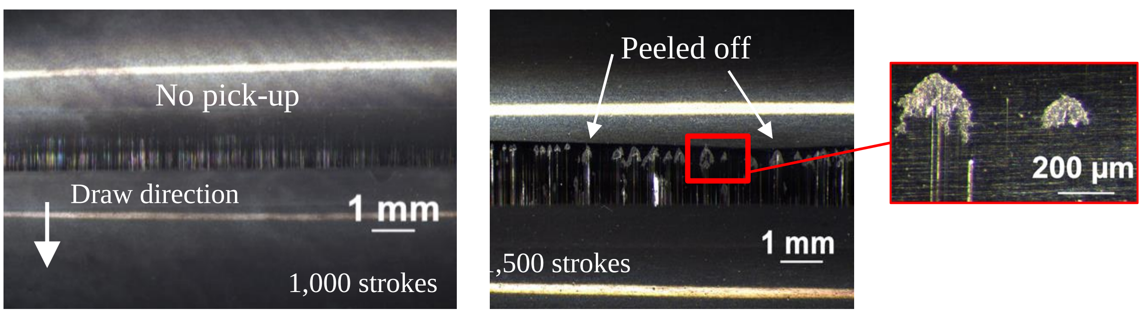
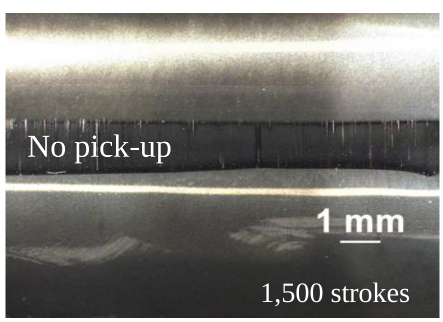



Figure 11: Surface roughness Ra and formed sheet surface condition after drawing the stainless steel under (a) dry and (b) lubricated conditions.




(a) (b)




(c)

Figure 12: Tool surface appearance after (a) 1,000 strokes in dry condition, and 1,500 strokes for (b) dry and (c) lubricated conditions.

### 4.5 Numerical simulation of strip reduction test

A numerical analysis of the strip reduction test was performed with LS-DYNA v. R7.1.1 using implicit time integration. Figure 13 shows the FE model of the strip reduction assuming plane strain with 1,969 linear quadrilateral elements. Due to symmetry, only half of the process is modelled. A fine, uniform mesh was applied in the contact between the workpiece and the tool surface. The tool was modelled as an elastic object, while the workpiece was treated as an elastic-plastic object of stainless steel sheet material EN1.4307 according to Voce's stress-strain curve described in Figure 7.

The test parameters adopted were similar to the ones listed in Table 1. The numerical simulation coupled a mechanical and a thermal analysis, simulating one stroke only. The mechanical and thermal properties applied are listed in Table 4 and Table 5, respectively. The Heat Transfer Coefficient HTC between the tool and the workpiece surface was assumed to be 40 kW/m2K, replicating a thermo-mechanical simulation of strip reduction testing studied by Olsson et al. (2004). The initial temperature of the tool and workpiece were both assumed to be 20 °C. The Coulomb friction model was used for the surface contact between the tool and the workpiece. The coefficient of friction μ was determined by matching experimental and theoretical drawing load. Figure 14 shows the outcome of this, which resulted in μ = 0.4 and μ = 0.2 for dry and lubricated conditions, respectively.

Table 4: Material properties of the test materials.

| **Components** | **Mechanical Properties** | | |
|---|---|---|---|
| | **Density *ρ* (g/cm³)** | **Poisson ratio *ν*** | **Elastic modulus *E* (GPa)** |
| Tool (Vanadis 4) | 7.56 | 0.3 | 200 |
| Workpiece (EN1.4307) | 7.90 | 0.3 | 200 |

Table 5: Thermal properties of the test materials.

| **Components** | **Thermal Properties** | | |
|---|---|---|---|
| | **Initial temperature $T_i$ (°C)** | **Heat capacity (J/(kg.K))** | **Thermal conductivity (W/(m.K))** |
| Tool (Vanadis 4) | 20 | 460 | 26 |
| Workpiece (EN1.4307) | 20 | 500 | 15 |

Figure 9.15(a) shows the normal pressure distribution along the contact region, reaching a maximum of 900-1000 MPa with no significant difference between dry and lubricated conditions. Fluctuations in the normal pressure values could be caused by irregular meshes in the tool/workpiece contact, Figure 13. However, as seen in Figure 15(b), higher temperature at the tool/workpiece interface is predicted in the dry condition than the lubricated one, which is due to higher friction, see Figure 14. The temperature increase ΔT along the tool/workpiece interface is thus reduced by lubricating, and even the plain mineral oil without special additives applied results in prevention of galling.

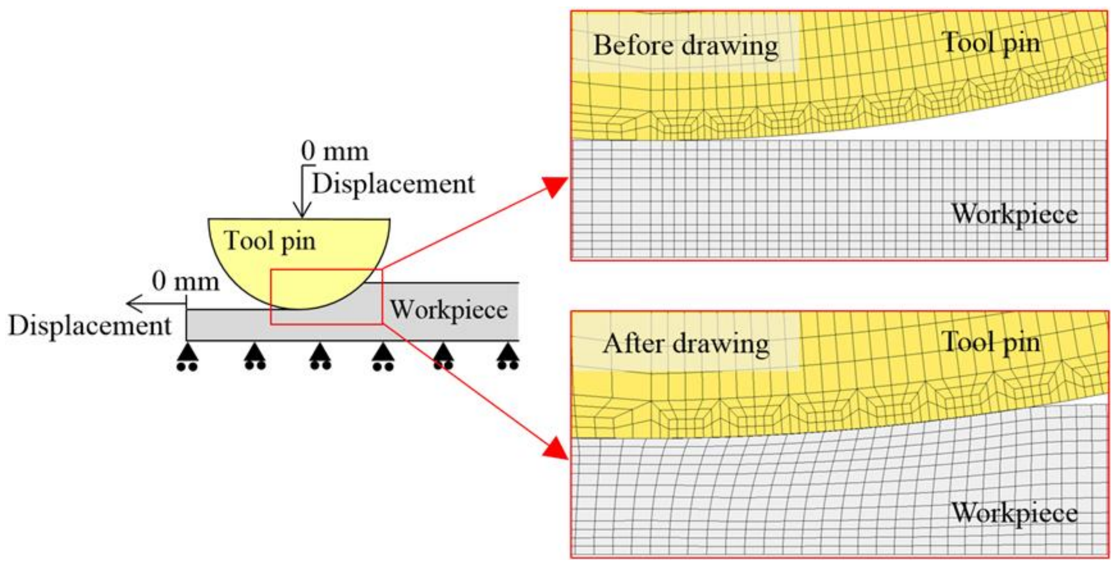



Figure 13: Numerical model of the strip reduction (left) and mesh elements of the numerical model in the tool/workpiece contact (right).

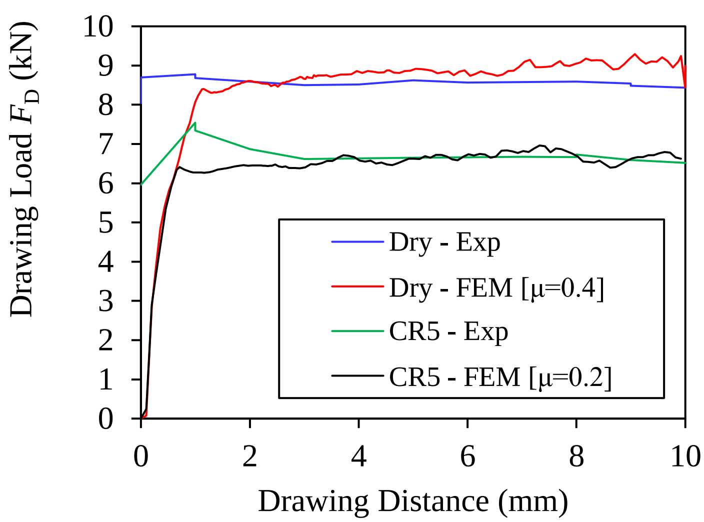
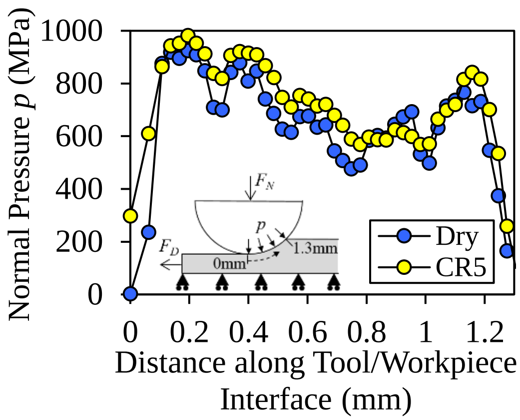
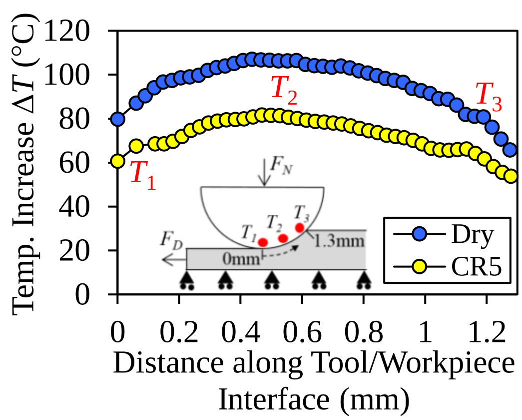



Figure 14: Experimental and numerical drawing loads at 1,500 strokes.




(a)




(b)

Figure 15: (a) Normal pressure and (b) temperature distributions along the tool-workpiece interface in strip reduction.

## CONCLUSION

The present study adopted the strip reduction test to evaluate two double-layer coating structures deposited on the tool surface for ironing of stainless steel cups. The two coatings comprised of DLC/Hyperlox® and Hyperlox®/Hyperlox®. The experiments revealed that DLC/Hyperlox® worked satisfactorily in all test conditions provided that a minimum amount of lubrication was utilized to avoid peeling off of the coating. A numerical analysis supports the experimental findings, where lubrication is necessary to reduce the temperature increase at the tool/workpiece interface by reducing the friction.

## ACKNOWLEDGEMENT

The work is supported by the Danish Council for Independent Research (Grant no.: DFF–4005–00130). Mohd Hafis Sulaiman would like to thank the Universiti Malaysia Perlis, the Ministry of Education, Malaysia, and the Taiho Kogyo Tribology Research Foundation (TTRF), for providing financial assistance (Grant no: 9009-00059). The authors gratefully acknowledge the support from Allan de Neergaard, CemeCON Scandinavia A/S for providing the coatings.

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