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Tribological Characteristics of Non-Chlorinated Metalworking Fluid in Stainless Steel Deep Drawing

Pramote Koowattanasuchat[1], Sasawat Mahabunphachai[2], Sukunthakan Ngernbamrung[2], and Numpon Mahayotsanun[1,*]

[1] Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen 40002
[2] National Metal and Materials Technology Center (MTEC), Thailand Science Park, Pathum Thani 12120
*Corresponding Author: numpon@kku.ac.th, +66-87-554-2879, Fax. +66-43-202-849

Abstract

This study was experimentally carried out to observe the tribological performance of the non-chlorinated lubricant in stainless steel deep drawing. This specially formulated lubricant with no chlorine additive was compared with the one having chlorine additive in the strip drawing test. The tool and sheet materials were SKD11 and AISI 304, respectively. The contact pressure, sliding velocity, and bending angle were varied to determine the differences in the friction coefficients and amounts of wear occurring on the die surfaces. The results showed that the friction coefficients of the non-chlorinated lubricant were close to those of the chlorinated lubricant at 9.375 MPa contact pressure, 10 mm/min sliding velocity, and 0º bending angle. The results obtained from this study could be used to formulate new alternative lubricants and select suitable conditions in stainless steels deep drawing.

***Keywords**:* Deep Drawing; Non-Chlorinated Lubricant; Stainless Steel; Tribology

1. Introduction

The trends in stainless steel deep drawing require products having complex shapes, high depths, small radii, and fine surface finish. One of the major concerns in forming these parts is the lubrication between the tool and the sheet, which must allow the sheet to flow properly without causing damage to the tool surface. In general, metalworking fluids having extreme pressure (EP) additives are effective in friction reduction, which leads to the tool life extension and energy reduction [1-6]. Chlorinated additives help reduce friction between sheet and tool under the influence of temperature and pressure [7-10]. Andreasen et al. [7] investigated the lubricant film breakdown and subsequent galling of different lubricants by using the strip reduction test and found out that lubricants with chlorine generally performed better than the other lubricants did. Petrushina et al. [9] examined the chemical activity and surface layer of several EP additives in the strip reduction test of stainless steel and found out that chlorine enforced the formation of a thick oxide layer. However, metalworking fluids having a certain amount of chlorine levels are considered hazardous wastes.

As a result, there have been many efforts to develop alternative lubricants that are human and environmental friendly, and still offer similar or better tribological performances than chlorinated oils [12-21]. Bay et al. [16] summarized potential materials and methods to replace environmentally hazardous lubricants in metal forming and suggested alternative additives and vegetable oils. Nagendramma [17] provided an overview of how ecofriendly lubricants could be developed and also pointed out that synthetic polyol esters could be used as metalworking fluids. Quinchia et al. [21] studied the tribological performances of different vegetable oils and found out that certain lubricants were effective in friction and wear reduction in specific lubrication regimes.

This research aimed to investigate the tribological performance of the specially formulated oil that contained no chlorine additive in comparison with the one having chlorine additive. It was hypothesized that the performance of this specially formulated oil could be similar to that of the chlorine additive one at certain operating conditions. The strip drawing test was used to determine the friction coefficients of the lubricants at the tool-sheet interface. The wear observations on the tool surfaces were also conducted. The results obtained from this study would be helpful to formulate new alternative and non-hazardous lubricants, particularly for deep drawing of stainless steel sheets such as kitchen sinks production. The suitable forming conditions for these lubricants could also be suggested based on the experimental results.

2. Strip Drawing Test

The strip drawing test was developed to simulate a sheet metal forming process and to measure the friction coefficients between the tool (blankholder, die) and sheet as illustrated in Fig. 1. In this apparatus, the bending angle (θ) can be adjusted in three configurations (0º, 45º, and 90º), which provided the ability to understand tribological behaviors while forming complex shapes.

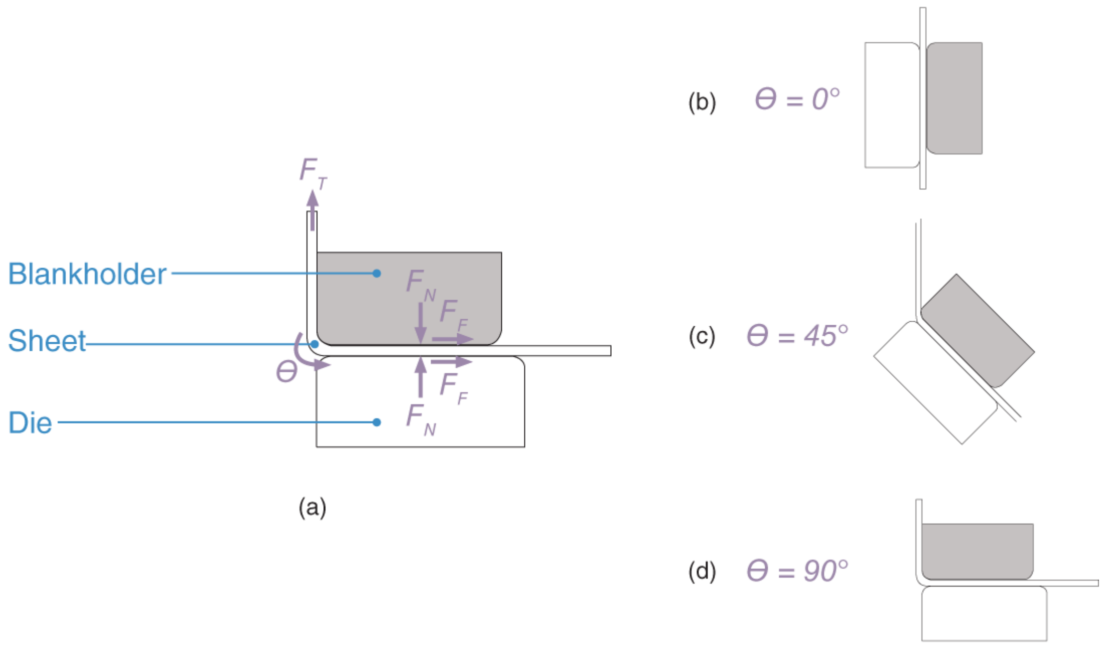

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Fig. 1 Schematic of the strip drawing test: (a) major parts and considered forces; (b) Θ = 0º; (c) Θ = 45º; and (d) Θ = 90º

During the test, a sheet was placed in between the blankholder and the die and pulled vertically upward. The tension force (F_T) and normal force (F_N) were recorded during the entire sliding distance and the friction coefficient (μ) could be obtained by Eq. 1.

$$\mu = F_T/(2F_N) \qquad (1)$$

Note that the materials and surface finishing of both blankholder and die were the same. As a result, the friction force (F_F) was assumed to be the same for both blankholder-sheet interface and die-sheet interface. Throughout this study, the considered interface was regarded as tool-sheet.

3. Materials

The considered tool and sheet materials and their properties are presented in Table 1. The tool was prepared by machining and surface polishing. The surface of the tool was also coated by vanadium carbide (VC) through thermal diffusion process. The sheet was prepared by laser cutting. The surface roughness (Ra) of the tool and the sheet was approximately 2.3 µm. Two specially formulated lubricants were used in this study and their properties are presented in Table 2. Note that these two lubricants were formulated to have similar properties except the presence of chlorine additive.

Table. 1 Material properties of the investigated tool and sheet

Part	Dimension [mm x mm x mm]	Material	Yield Strength [MPa]	Tensile Strength [MPa]	Elongation [%]	Hardness [HRC]
Tool	20 x 30 x 40	SKD11	-	-	-	58-62
Sheet	0.9 x 10 x 948	AISI 304	305	734	50	-

Table. 2 Properties of the tested lubricants

Lubricant	Additive	Appearance	Specific Gravity [g/cm^3, 15ºC]	Viscosity [mm^2/s, 40ºC]	Copper Corrosion Test [100ºC x 1hr]	Application
Chlorinated oil (Cl)	Sulfur, Chlorine	Dark brown transparent	0.92	126	4 (Active)	Forming oil
Non-chlorinated oil (NCl)	Sulfur	Dark red transparent	1.00	135	2 (Inactive)	Forming oil

Table. 3 Testing conditions to investigate considered factors

Considered Factors	Testing Conditions			
	Lubricant	Contact Pressure [MPa]	Sliding Velocity [mm/min]	Bending Angle [º]
Contact Pressure	CI NC	3.125 MPa 6.250 MPa 9.375 MPa	10	0
Sliding Velocity		6.250 MPa	10 100	0
Bending Angle (θ)		6.250 MPa	100	0º 45º 90º

4. Testing Conditions

Prior to the strip drawing tests, all the sheet samples were cleaned by using detergent and dried in air to remove any oil or grease on the surfaces. In each testing condition, the tested lubricant was evenly applied on the both sides of the sheet sample. To ensure that the amounts of lubricant were similar for all the conditions, only one brush stroke of lubricant was carefully applied on each side of the sheet surface. The tools were also cleaned by acetone and let dry to remove any existing lubricant. During the test, the sheet sample was placed between the tools and compressed by a set contact pressure. The top part of the sheet was pulled vertically upward 300 mm with a set sliding velocity. The tension force, normal force, and sliding distance data were captured to obtain the friction coefficient of the tool-sheet interface. After each test, wear on the tool surfaces was observed by using scanning electron microscope (SEM). Then the tool surfaces were carefully cleaned and polished by fine diamond solutions in order to remove any adhesion and to keep the original surface characteristics as much as possible. The cleaned tool surfaces were monitored again with SEM to determine the surface characteristics. If the cleaned surfaces varied greatly from their original surfaces, a new set of tools were used in later runs. A new cleaned sheet was always used in every test. Note that three repeated trials were carried out in each condition and the average friction coefficient values were used for comparison.

In this study, three main factors were considered: (1) contact pressure, (2) sliding velocity, and (3) bending angle. The strip drawing test conditions in this study are presented in Table 3.

5. Results and Discussions

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The effects of the contact pressure on the considered lubricants can be seen in Fig. 2. In general, the friction coefficients of the non-chlorinated oil were higher than those of the chlorinated oil (up to 100% increase at 6.250 MPa). This was due to the fact that chlorine reacted on the metal surfaces and formed a layer that helped support the load. When the contact pressure increased, the friction coefficients of the chlorinated oil tended to decrease slightly. This could be because of the decrease in oil thickness due to increasing pressure, which helped reduce fluid drag in hydrodynamic lubrication. However, a different behavior was observed in the non-chlorinated oil. When the contact pressure increased from 3.125 MPa to 6.250 MPa, the friction coefficients of the non-chlorinated oil kept increasing along the sliding distance. This amount of contact pressure at 10 mm/min sliding speed might have caused the lubricant film to breakdown, leading to increasing surface contact along the sliding distance. If the contact pressure was increased further to 9.375 MPa, the friction coefficients were reduced to those of the chlorinated lubricant. At high contact pressure, the non-chlorinated oil thickness was reduced but seemed to able to form and separate the surface contact better than at lower contact pressures.

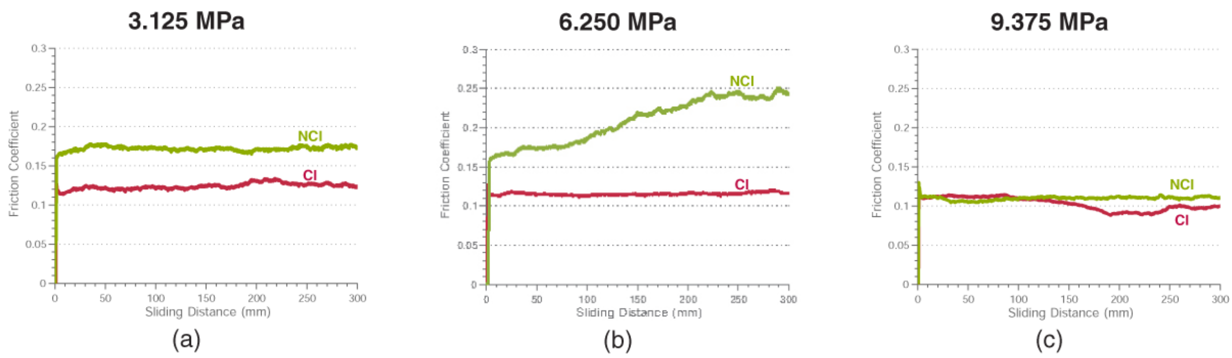

Fig. 2 Friction coefficient vs. sliding distance of the two lubricants carried out at 10 mm/min and θ = 0º: (a) 3.125 MPa; (b) 6.250 MPa; and (c) 9.375 MPa

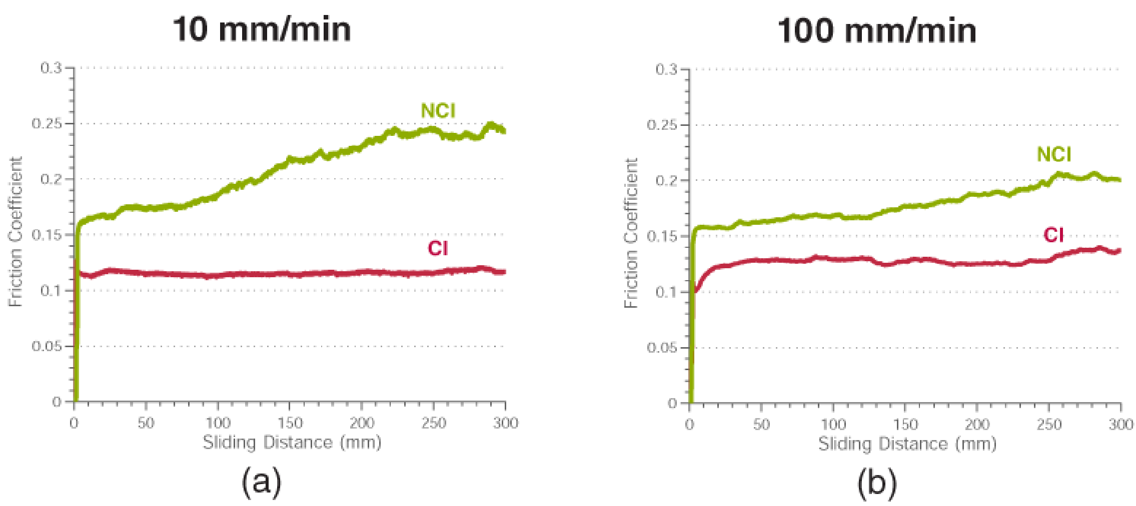

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Fig. 3 Friction coefficient vs. sliding distance of the two lubricants carried out at 6.250 MPa and θ = 0º: (a) 10 mm/min; and (b) 100 mm/min

The effects of the sliding velocity on the considered lubricants can be seen in Fig. 3. The chlorinated oil performed better than the non-chlorinated oil at both sliding velocities. The friction coefficients of the chlorinated oil did not seem to be significantly affected by the sliding velocity. As for the non-chlorinated oil, the friction coefficients kept increasing along the sliding distance. This also implied that the non-chlorinated oil could not form a layer separating the surfaces over the entire sliding distance. However, the friction coefficients of the non-chlorinated oil reduced with increasing sliding velocity. This could be due to the fact that the oil film began to form and acted to support load at this sliding velocity. In order to determine if the friction coefficients of the non-chlorinated oil would reduce further at higher sliding velocities, more experiments must be carried out.

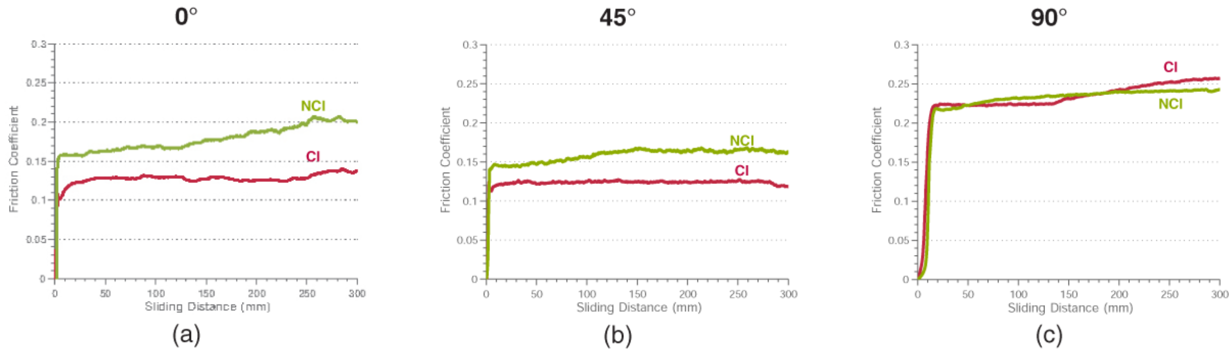

Fig. 4 Friction coefficient vs. sliding distance of the two lubricants carried out at 6.250 MPa and 100 mm/min: (a) θ = 0º; (b) θ = 45º; and (c) θ = 90º

The effects of the bending angle on the considered lubricants can be seen in Fig. 4. It could be clearly observed that the friction coefficients of both lubricants were highest at 90º and lowest at 45º. Based on previous studies on sheet bending [22-24], the contact pressure around the die radius was non-homogenous and found to have low contact pressure at around 45º. This could be explained by the outward distortion of the sheet (anticlastic), which left the 45º section with small contact area [25]. As a result, the forces required to overcome friction at 45º were also low, leading to decreased friction coefficients. This implied that the high contact pressure caused by 90º bending angle significantly reduced the oil thickness, which could not act to support the load. Increasing the bending angle from 0º to 45º, the friction coefficients of the chlorinated oil were not significantly changed. However, the friction coefficients of the non-chlorinated oil decreased with this change. Again, this could also be explained by the effect of outward distortion of the sheet. Overall, the chlorinated oil performed better than the non-chlorinated oil when the bending angle varied.

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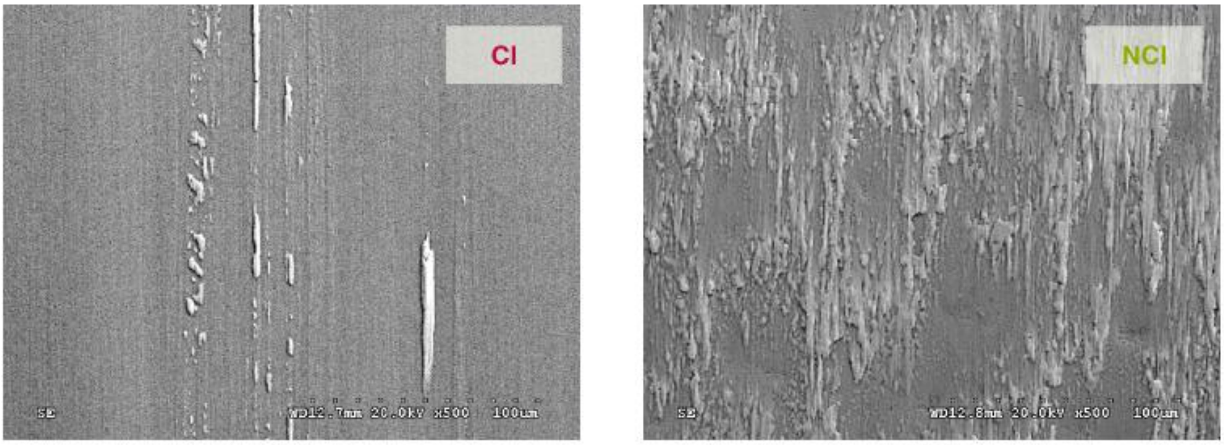

(a) (b)

Fig. 5 Wear observations on the tool surfaces carried out at 6.250 MPa, 100 mm/min, θ = 45º: (a) chlorinated oil (Cl); and (b) non-chlorinated oil (NCl)

Wear observations on the tool surfaces after the strip drawing tests are shown in Fig. 5. It could be observed that amounts of adhesion on the tool surfaces under non-chlorinated oil were much higher than those of the chlorinated oil. This also confirmed that the non-chlorinated oil could not support the load during the strip drawing test, which was in agreement with the higher friction coefficients.

Overall, the friction and wear performances of the specially formulated oil with no chlorine additive were still not comparable to those of the chlorinated oil. Only in some specific condition (9.375 MPa, 10 mm/min, and 0º bending angle) that the performance of the non-chlorinated oil was close to that of the chlorinated oil. More experiments must be carried out to observe the tribologicial performances of the non-chlorinated oil, particularly at higher sliding velocities, which was a favorable condition in forming process. Nevertheless, the results obtained from this study provided a guideline for more research works in the development of new environmental friendly lubricants.

6. Conclusions

The strip drawing tests were carried out to investigate the tribological performance of the non-chlorinated oil in comparison with the chlorinated oil. The tested die and sheet were SKD11 and AISI 304, respectively. The contact pressure, sliding velocity, and the bending angle were varied to observe the tribological performances of the oils in various operating conditions. The results showed that the non-chlorinated oil provided higher friction coefficients in most of the testing conditions. However, when the contact pressure was 9.375 MPa, the sliding velocity was 10 mm/min, and bending angle was 0º, the friction coefficients of the non-chlorinated oil were similar to those of the chlorinated oil. Although the non-chlorinated oil could be used in real application at this specific operating condition, there were still rooms of improvement to formulate the non-chlorinated oil for other operating conditions, particularly at high contact pressure, high sliding velocity, and some degrees of bending angle.

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