Study on the Lubrication Performances of Rolling Oil for Cold Rolled Laminated Cu/Al Composite Sheet

Sang Xiong¹, 2, 3, *, Zhengping Shang¹, a, Huan Gao¹, b and Qijie Zhai², c

¹ Jiangsuzhongse Composite Materials Co., LTD., Wuxi 214000, China
² School of Materials Science and Engineering, Shanghai University, Shanghai 200000, China
³ College of Materials Science and Engineering, Nanjing Institute of Technology, Nanjing Jiang Su 211167, China

* Corresponding author: jxbjxs2008@163.com, a 641483235@qq.com, b 411622074@qq.com, c 1271800877@qq.com

Abstract. Three kinds of ester base oils (D85, D100, D115), dodecyl alcohol, dodecyl acid, butyl stearate as oiliness agents, and thiophosphate, fatty alcohol phosphates and dibutyl phosphate as extreme pressure agents were used to prepare and investigate the tribological properties of rolling oils for cold rolled laminated Cu/Al composite sheet by an orthogonal experiment, and lubrication performances of the rolling oils were studied through rolling experiments. Surface roughness and the interface of Cu/Al composite sheet were analyzed. The results show that the optimum tribological properties of the rolling oil is compose of D100 as basic oil, butyl stearate as oiliness agent and the compound ratio of fatty alcohol phosphates and thiophosphate of 3:1 as extreme pressure antiwar agent. The PB value reaches 1020 N, the coefficient of friction is 0.0795. Basic oil is the main factor of rolling capacity. The rolling oil contented D115, showed the best rolling capacity while the minimum thickness was only 0.045mm. The addition of butyl stearate improved the surface quality of both copper and aluminum side of the rolled stripes and make the sheet surface roughness decreased. After cold rolling, new composite interface, which is clear and tightly bound replaced the brittle mesophase.

Key words: Cu-Al composite sheet; lubrication; cold rolling; surface topography.

1. Introduction
This document was prepared using the AIP Proceedings template for Microsoft Word. It provides a simple example of a paper and offers guidelines for preparing your article. Here we introduce the paragraph styles for Level 1, Level 2, and Level 3 headings. Cu-Al composite sheet have attracted much attention in recent years, such as high conductivity, high thermal conductivity, low contact resistance and light weight and corrosion resistance of aluminum [1, 2]. It is widely used in aviation, aerospace, machinery, medical treatment, food, civil and other fields [3]. In the rolling process of Cu-Al composite sheet, effective lubrication could reduce the minimum rolling gauge, improve the surface quality of the product, prolong the service life of the casting roll and reduce energy consumption [4]. In the process
of cold rolling, due to the close contact between the roller and the workpiece, friction and wear will inevitably occur, increasing the energy loss. The lubricant containing phosphorus and sulfur can form a lubricating film on the workpiece and reduce the friction and wear in the rolling process [5]. With the emergence of high-precision Cu-Al composite sheet technology, an opportunity is provided to develop a new kind of cold rolling oil and to solve the above-mentioned problems [6]. The reasonable selection of base oil and additives is crucial for rolling of Cu-Al composite sheet under the same condition.

The present work focuses on the assessment of the effect of different base oils (D85, D100, D115), oiliness agents (dodecyl alcohol, dodecyl acid, butyl stearate) and three ratios of the various extreme pressure agent on the rolling oil lubrication property of Cu-Al composite sheet. Therefore, the tribological properties of rolling oils, the lubrication performance and the surface quality of the rolled Cu-Al composite sheet were studied. Furthermore, this work can offer a reference for the development of high-precision Cu-Al composite sheet technology in the future.

2. Experiment and Method

2.1. Materials

Here is how to display a pop-up window from which to select and apply the AIP Proceedings template paragraph styles. Pure copper (T2) and aluminum (1060) were used in the experiment and the chemical compositions are listed in Table 1. Three kinds of ester base oils (D85, D100, D115), dodecyl alcohol, dodecyl acid, butyl stearate as oiliness agents, and thiophosphate, fatty alcohol phosphates and dibutyl phosphate as extreme pressure agents were used. The flash points of the D85, D100 and D115 are 85, 100 and 115℃, respectively. At 40℃, kinematic viscosities of D85, D100 and D115 are 2.0 mm²·s⁻¹, 2.5 mm²·s⁻¹ and 3.0 mm²·s⁻¹. Orthogonal design of four factors and three levels was taken to obtain the proper agents and given in Table 2 and Table 3. The rolling oils were consisting of base oil 90%, oiliness agents 9.6% and extreme pressure agents 0.4%. Heat the base oil to about 40℃, add oily agent and extreme pressure agent and stir, make rolling oil mix evenly.

| Elements | Cu | Pb | S | Cd | P | Fe |
|----------|----|----|---|----|---|----|
| T2       | 99.9900 | 0.0003 | 0.0016 | 0.0002 | 0.0013 | 0.0009 |
| Elements | Fe | Mn | Mg | Si | Zn | Ti | Cu | Al |
| 1060     | 0.35 | 0.03 | 0.03 | 0.25 | 0.05 | 0.03 | 0.05 | 99.21 |

Table 1. Chemical compositions of Cu-Al composite sheet (Atom%)
Table 3. Orthogonal test table L9 (3^4)

| Samples | A Types of base oils | B Types of oiliness agents | C Types of extreme pressure agents | D Extreme pressure agents ratios |
|---------|---------------------|-----------------------------|-----------------------------------|-------------------------------|
| 1#      | 1                   | 1                           | 1                                 | 1                             |
| 2#      | 1                   | 2                           | 2                                 | 2                             |
| 3#      | 1                   | 3                           | 3                                 | 3                             |
| 4#      | 2                   | 1                           | 2                                 | 3                             |
| 5#      | 2                   | 2                           | 3                                 | 1                             |
| 6#      | 2                   | 3                           | 1                                 | 2                             |
| 7#      | 3                   | 1                           | 3                                 | 2                             |
| 8#      | 3                   | 2                           | 1                                 | 3                             |
| 9#      | 3                   | 3                           | 2                                 | 1                             |

2.2. Test on Tribological Properties

An MRS-10A four ball testing machine was used according to the national standard GB/T 12583—1998 to measure the maximum non-seizure load ($P_B$ value) adopted for estimating the load carrying capacity of the rolling oils. The average coefficient of friction of different rolling oil samples was obtained from experiments conducted in 30 minutes of testing at room temperature under a loading force of 147 N, a rotational speed of 1 200 revolutions per minute. Each experiment was measured three times.

2.3. Cold Rolling Test

A four-high rolling mill of Φ95/200 mm×200 mm with a velocity of 60 r/min and a rolling power of 35 kW was used to evaluate the lubricity of the rolling oils. The workpiece thickness was 1.0 mm and the pass-reduction was 20%. The surface morphology analyses of rolled copper foil were conducted by an FTS-S3c roughness instrument and LEICA metalloscopy. The interface of Cu/Al composite sheet was analyzed by a scanning electron microscope (SEM).

3. Results and Discussions

3.1. Tribological Properties

$P_B$ is an important parameter that reflects the load carrying capacity of rolling oil, which is determined by the rolling oil viscosity, the adsorption film toughness and the sliding speed. $P_B$ and the coefficient of friction are two important indexes of extreme pressure and antiwear performance of the rolling oil. The bigger the $P_B$ value is, the stronger oil film and better anti-wear and friction-reducing performance of the rolling oil will be. Similarly, the smaller the coefficient of friction is, the better the lubricity will be. However, the two factors are not always coincident. For the convenience of the analysis, an extreme pressure and anti-wear coefficient ($\omega$) that can combine the $P_B$ value and the coefficient of friction with the same standards to reflect the tribological properties of rolling oil directly, as shown in Eq. (1).

$$\omega = 10 \log_{10} \left( \frac{P_B}{\mu} \right)$$

(1)

Where $P_B$ is the maximum non-seizure load, and $\mu$ is the coefficient of friction.

The values of $P_B$, $\mu$ and $\omega$ from the tribological results of orthogonal experiment are given in Table 4. Employing the method of orthogonal trial with mixed types of agents and processing the data with range analyze and listed in Table 5.
Table 4. Tribological test of orthogonal experiment

| Samples | Effects | $P_\mu/N$ | $\mu$ | $\omega$ |
|---------|---------|----------|-------|----------|
| 1#      | A 1 B 1 C 1 D 1 | 932      | 0.0602 | 4.190    |
| 2#      | A 2 B 2 C 2 D 2 | 412      | 0.0753 | 3.738    |
| 3#      | A 3 B 3 C 3 D 2 | 932      | 0.0697 | 4.126    |
| 4#      | A 2 B 2 C 3 D 1 | 883      | 0.0803 | 4.041    |
| 5#      | A 2 B 3 C 1 D 2 | 696      | 0.0779 | 3.951    |
| 6#      | A 3 B 1 C 1 D 1 | 1020     | 0.0795 | 4.108    |
| 7#      | A 1 B 3 C 2 D 2 | 412      | 0.0768 | 3.730    |
| 8#      | A 3 B 2 C 1 D 1 | 784      | 0.0756 | 4.016    |
| 9#      | A 3 B 2 C 2 D 1 | 559      | 0.0788 | 3.851    |

Table 5. Range analyzes of orthogonal experiment

| Samples | A Types of base oils | B Types of oiliness agents | C Types of extreme pressure agents | D Extreme pressure agents’ ratios |
|---------|----------------------|-----------------------------|------------------------------------|---------------------------------|
| k1j     | 4.018                | 3.987                       | 4.105                              | 3.977                           |
| k2j     | 4.033                | 3.902                       | 3.877                              | 4.061                           |
| k3j     | 3.866                | 4.028                       | 3.936                              | 3.859                           |
| Rj      | 0.167                | 0.126                       | 0.228                              | 0.202                           |
| Order   | C>D>A>B              |                             |                                    |                                 |
| Optimal level | A_2          | B_3                       | C_1                   | D_2                       |
| Optimal portfolio | A_2B_3C_1D_2     |                            |                        |                                |

In Table 5, $K_{ij}$ refers to the cumulative results of experimental data processing of different $j$ factors at the same level in each group. $j$ factors include A, B, C and D factors, and i levels include 1, 2 and 3. $R_j$ represents range, that is, the difference between the maximum value and minimum value of each $K_j$ value in factor $j$. The larger the $R_j$, the more obvious the influence of $j$ factor in the orthogonal table on the experimental results. It can be seen from the table that the types of extreme pressure agents play a major role in increasing oil film strength and reducing wear of sheet and strip. From the influence of extreme pressure agent ratio D, it can be seen that the ratio of different extreme pressure agent has a certain effect on the rolling oil lubrication properties, presumably related to the type of extreme pressure agent. After the compound of thiophosphate and fatty alcohol phosphates, the oil film strength was increased to the highest level, and the compound synergistic effect was played in the base oil. From the above, the optimum tribological properties of the rolling oil is compose of D100 as basic oil, butyl stearate as oiliness agent and the compound ratio of fatty alcohol phosphates and thiophosphate of 3:1 as extreme pressure antiwear agent. The PB value reaches 1020 N, the coefficient of friction is 0.0795. Basic oil is the main factor of rolling capacity.

3.2. Lubrication Performance of Rolling Oil

The rolling thickness of Cu-Al composite sheet with 20% reduction per pass using different lubricating oils are shown in Fig. 1. It can be clearly seen from the Fig. 1 that the rolling oil of sample 2# and sample 3# has the maximum rolled thickness, the minimum draft, while the rolling oil of sample 6# and sample 7# has the minimum rolling gauge and the maximum draft is 0.955 mm. The rolled thickness is calculated to the formula,

$$h = \frac{4.148K_\mu D\sqrt{e}}{E}$$ (2)

...
where E is elasticity modulus, N/mm², K is resistance to deformation, N/mm², µ is coefficient of friction, D is the roll diameter, mm and \( \frac{D}{E} \) is relative pressure, %. It can be concluded that sample 6# and sample 7# have the best lubricity during rolling.

**Figure 1.** Thickness of Cu-Al composite sheet under different lubrication conditions

The parameter \( R_a \) (mean height of profile irregularities) is used to characterized the surface roughness of rolled Cu-Al composite sheet and Fig. 2. It is confirmed that the surface roughness of Cu-Al composite sheet is affected by the types of oiliness agents, and ester oil agents have a greater influence on the surface of Al side and Cu side. The rolling oil mixed with the oily agent butyl stearate has good lubrication effect on the copper and aluminum layers, that is to say, it plays an excellent role in wetting and friction reduction during the lubrication process. The surface roughness \( R_a \) of Cu side lubricated with the sample 6#, 7# and 9# containing butyl stearate as oiliness agents were only 0.199 µm, 0.427 µm and 0.143 µm, respectively.

**Figure 2.** Rolled surface roughness curve lubricated with the rolling oils

Surface morphology of Cu side lubricated with the rolling oils and given in Fig. 3. It is obvious that the rolled surface has defects and deep scratches with the sample 7# lubrication, which are consistent with the results of surface roughness. A small amount of metal falling off and copper layer tearing perpendicular to the rolling direction can be observed. Sample 6# can effectively reduce the friction and wear of roller and Cu-Al composite sheet, which play a good role in lubrication, and ensure the smooth surface and uniform rolling texture after rolling. Sample 7# of the rolling oil has a higher viscosity and the oil film strength is higher than that of sample 6#, if the oil film thickness formed in the deformation zone exceeds the sum of the roughness of the roll surface and composite sheet, then the lubrication form
in the deformation zone will not be the typical boundary lubrication, but the fluid lubrication form. In this way, the rolling oil film will isolate the roller and rolling piece surface, there is no direct bite of the surface micro-convex body, but the rolled product surface becomes rough. Therefore, the optimum lubrication performance of the rolling oil is composed of D100 as basic oil, butyl stearate as oiliness agent and the compound ratio of fatty alcohol phosphates and thiophosphate of 3:1 as extreme pressure antiwear agent, which has the excellent lubrication effects, and the surface quality of rolled sheets is good.

Figure 3. Surface morphology of Cu side lubricated with the rolling oil sample 6# (a) and 7# (b)

Cu-Al intermetallic compounds of a certain thickness are easily formed at the composite interface after rolling. According to the Cu-Al phase diagram, the composition of this layer of intermetallic compounds are Al₂Cu, AlCu, Al₄Cu₉. The transition layer has an important effect on the composite quality of Cu-Al composite sheet. Generally, the transition layer at the interface should not be too thick, otherwise, the brittle intermetallic compound with low hardness at the interface will inevitably reduce the bonding strength and overall electrical conductivity of the Cu-Al composite sheet. Interfacial SEM images and interfacial composition curve of Cu-Al composite sheet are shown in Fig.4. There are obvious intermetallic compound layers at the Cu-Al interface of Cu-Al composite plate before rolling. The thickness of the intermetallic compound layer is about 1.9 μm. The hardness and brittleness of the intermetallic compound layer are relatively high. In the cold rolling process of Cu-Al composite plate, due to the low internal temperature, the diffusion velocity between copper and aluminum elements is very low, and it is difficult to form intermediate phase near the interface. Therefore, brittle Cu-Al intermetallic compound is effectively prevented, and the interface composite quality is improved to some extent. The relatively thick Cu-Al composite interface layer of the original plate was damaged and torn in the process of large deformation, and the Cu-Al materials were embedded into each other again. In Fig. 4b, there is an irregular light-colored narrow strip at the interface of the composite plate after rolling, which is caused by deformation heat generated by the cold rolling process with large deformation rate, resulting in a slight local diffusion process of copper and aluminum elements at the interface of the copper and aluminum composite plate after rolling, forming metallurgical bonding. Especially, The addition of butyl stearate improved the surface quality of both copper and aluminum side of the rolled stripes and make the sheet surface roughness decreased. After cold rolling, the brittle intermediate phase was replaced by a new composite interface with clear interface and tight binding.
Rolled interface lubricated with sample 6#

Figure 4. Interfacial SEM images and interfacial composition curve of Cu-Al composite sheet

4. Conclusion
Three kinds of ester base oils (D85, D100, D115), dodecyl alcohol, dodecyl acid, butyl stearate as oiliness agents, and thiophosphate, fatty alcohol phosphates and dibutyl phosphate as extreme pressure agents were used to prepare and investigate the tribological properties of rolling oils for cold rolled laminated Cu/Al composite sheet by an orthogonal experiment. The optimum lubrication performance of the rolling oil is composed of D100 as basic oil, butyl stearate as oiliness agent and the compound ratio of fatty alcohol phosphates and thiophosphate of 3:1 as extreme pressure antiwear agent, which has the excellent tribological properties. Lubrication performances of the rolling oils were studied through rolling experiments. Types of base oil is the main affecting factor to determine the rolling capacity of composite sheet among the parameters, D115 base oil with the highest viscosity exhibit the strongest ability of rolling, the optimal sample minimum rolling gauge is 0.045 mm. The rolling oil containing butyl stearate as oiliness agent has good lubrication effect on surface roughness of Al-Cu surface. It plays an excellent role in reducing friction during lubrication, and effectively improves the surface quality and reduces the surface roughness of the rolled Cu-Al sheet. Before cold rolling, Cu-Al composite sheet has brittle intermediate phase with thickness of 1.9μm. However, mesophase disappears at low temperature after cold rolling, forming a clear boundary and tight interface.

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