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Tribological behaviors between commercial pure titanium sheet and tools in warm forming

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Abstract: The tribological conditions between tools and sheet are the major factors affecting the product quality, forming limits and service life of tools in thin-walled titanium components warm forming. Using the orthogonal design based twist compression test in the temperature range of 25−300 °C, the significant factors affecting the coefficient of friction (CoF) and the influencing rules in CP-3 titanium sheet warm forming are clarified and discussed by changing tribological conditions such as tool material, lubrication, temperature and normal pressure. The results show that the significant factors affecting the CoF are lubrication, surface roughness, tool material, sliding velocity, normal pressure and temperature; compared with unlubricated condition, the graphite and MoS_2 greatly improve the friction condition and the maximum reduction of the CoF is 0.318; the CoFs of Cr12MoV/CP-3 and QAl10-3-1.5/CP-3 tribo-pairs show a similar tendency: the CoFs increase with increasing surface roughness and sliding velocity, and increase firstly then decrease with increasing normal pressure and temperature.

Key words: CP-3 titanium sheet; warm forming; lubrication; coefficient of friction

1 Introduction

Titanium and its alloys have been extensively used in aerospace, electronics, energy and biomedical applications due to their low density-strength ratio, high corrosion resistance and good biocompatibility [1]. In all of these fields, commercial pure titanium (CP-Ti) sheet metal forming is often used for manufacturing the components with light mass and high performance, such as aerospace fuel tanks which serve under harsh environments [2,3].

The CP-Ti usually exhibits limited ductility at room temperature because of its hexagonal close-packed (HCP) structure [4]. Warm forming is a feasible approach to reduce the deformation resistance of CP-Ti and improve its formability, and it has become an important method for the precision forming of the thin-walled titanium components [5−7]. However, constrained by high temperature and multi-tools, warm forming of CP-Ti sheet is too complex to be well controlled. And the friction and lubrication conditions between tools and CP-Ti sheet are the major factors affecting this process, which mainly determine the forming quality, forming limits and the service life of tools. Therefore, suitable friction and lubrication conditions will effectively reduce the forming defects and improve the formability [8].

Up to now, regarding different materials and forming processes and using varieties of friction test methods, many researchers have studied the tribological behaviors in sheet metal forming and obtained many main parameters (surface roughness of tools, normal pressure, sliding velocity and temperature) affecting the CoF and their influencing rules.

LEE et al [9] studied the influence of surface roughness of electric galvanized steel sheets on friction by tensile test, surface roughness test and friction test with drawing oils. The test results showed that the CoF was high when surface roughness was extremely small or high. CRISTINO et al [10] used pure lead and AISL

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316L steel to study the effect of surface roughness on friction by a ring compression test. They found that the CoF was changed as “S” curve with increasing surface roughness of lead.

SZAKALY and LENARD [11] used the flat-die test to study the effects of process parameters on the CoF. ExtraGal™, bare steel and HDG steel were used in the tests. The result showed that the effect of normal pressure on friction was related to the tool roughness. When using the tools with high roughness, all the three steels indicated that the CoF increased with increasing normal pressure. While using the smooth tools, they presented an opposite tendency.

SAVASKAN and ALEMDAĞ [12] studied the effect of sliding velocity on the CoF in the tribo-pair Al−40Zn−3Cu−2Si alloy/SAE 65 using the block-on-disc test. They concluded that the sliding velocity showed little influence on the CoF. Other researchers suggested that the CoF decreased with increasing the sliding velocity, using the flat-die test, and they explained reasons for the changing trends from the perspective of lubrication and metals bonds [11,13,14].

MALE [15] used several kinds of tribo-pairs to investigate the effect of temperature on the CoF. The results showed that the changing trends of CoFs depended on the materials of tribo-pairs. And similar results can also be seen in present research that the CoFs of most tribo-pairs materials showed a decreasing trend in a certain temperature range [16,17].

However, the current studies mainly aim at the common metals (steel and aluminum) with simple factors considered, and the influences on the friction are mostly obtained at room temperature. The tribological behavior affected by multi-factors in sheet metal forming is still a nontrivial issue, especially for light mass and high performance titanium alloy sheet forming at elevated temperature.

It is known that the simulative friction tests can effectively simulate different tribological conditions in practical production by changing testing parameters. And there are varieties of friction test methods developed for sheet metal forming, such as the flat-die test, the pin-on-disk test and the twist compression test (TCT) [11,18−20]. Nevertheless, the TCT has been widely used due to its wide consideration of factors, good versatility and accurate measurements. Thus, in this work, by developing an instrumented high temperature TCT, the significant factors affecting the CoF in thin-walled CP-Ti sheet warm forming were determined by orthogonal design method firstly. Based on this, the influencing rules of various significant factors on the CoF were clarified and discussed.

2 Experimental

2.1 Experimental procedure

The high temperature TCT was used for investigating the tribological behaviors in CP-Ti sheet warm forming. Figure 1 shows the device of TCT and the corresponding samples. In this test, an annular cylinder specimen (upper specimen) was lowered under hydraulic pressure and contacted with a flat specimen (lower specimen) that was cut from CP-3 sheet. Then, the annular specimen rotated with a constant velocity against the flat one when the pressure and temperature reached the preset values. In this friction process, the transmitted torque between rotating cylinder and the flat specimen was measured accurately. According to the Coulomb law, one classical theoretical model in sheet metal forming [21], the CoF can be calculated from the ratio of friction force F to applied normal pressure P as follows:

$$\mu=\frac{F}{P}=\frac{T}{rPA} \tag{1}$$

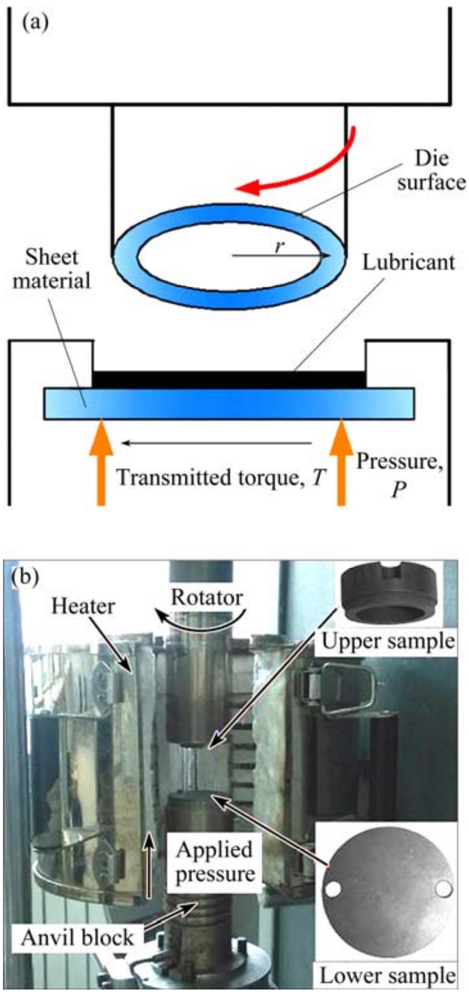

Fig. 1 High-temperature TCT friction test: (a) Schematic of test; (b) Setup of test

where μ is the CoF, F is the friction force between the tool and the sheet metal specimen, P is the normal contact pressure exerted by the tool on the sheet metal specimen, T is the friction twist torque transmitted from the tool to the sheet metal specimen, r is the mean radius of the tool, and A is the cross-sectional area of the annular tool.

2.2 Materials

The specimens chosen for the experiments include an annular cylinder specimen and a flat specimen. The flat specimens, 1 mm in thickness, were cut from the CP-3 sheet with a surface roughness of 0.8 μm. Table 1 shows the chemical composition of CP-3 sheet. Three materials were chosen for the annual cylinder specimens. One of them, Cr12MoV steel with high hardenability, was commonly used for hot-working process. Another QAl10-3-1.5, an aluminum bronze alloy with good wearability, and 45 steel, a medium-carbon steel were also used. The mechanical properties such as tensile strength and the applicable temperature ranges are given in Table 2. According to the performance of various tool materials, both of them can be selected as the alternative tool materials for CP-3 sheet warm forming.

Table 1 Chemical composition of CP-3 sheets (mass fraction, %)

C	O	Fe	N	H	Other (total)	Ti
0.10	0.25	0.20	0.05	0.015	0.15	Bal.

Table 2 Mechanical properties and applicable temperature of tool samples

Material	$\sigma_{0.2}$/MPa	σ_b/MPa	Hardness/MPa	Temperature/°C
Cr12MoV	785	930	831	≤400
QAl10-3-1.5	250	630	162	≤300
45 steel	355	600	404	≤400
CP-3	350	550	200	−

In order to investigate the effect of tool surface roughness on the tribological behaviors between tools and CP-3 sheet, the tools with different surface roughnesses were processed by machining and sandblasting methods. In search for the significant factors affecting the CoF, three different surfaces with roughnesses of 0.02, 0.8 and 6.3 μm were prepared for the orthogonal experiment. And in the study of influence of surface roughness on the CoF, six kinds of surface roughnesses (0.02, 0.2, 0.8, 1.6, 3.2 and 6.3 μm) were set.

2.3 Lubricants

During the CP-3 sheet warm forming process, there may appear some phenomena such as heavily sticking to tools, high heating rate and low thermal conductivity, thus, strict lubrication conditions are highly demanded. The use of lubricants is an effective approach to improve the friction and lubrication condition in sheet metal forming. The common lubricants can be clarified into base oil groups, semisynthetics, synthetics, dry-film lubricants and solid lubricants. In the present study, graphite lubricant and MoS_2 dry film lubricant were selected for CP-3 sheet warm forming, which can keep good lubricating performance in hostile working environment.

3 Results and discussion

3.1 Significant factors affecting tribological behaviors

In order to determine the significant factors affecting the tribological behaviors in CP-3 sheet warm forming, the orthogonal friction test with seven factors and three levels (3^7) was used in this work. Table 3 shows the influencing factors, levels and results of the orthogonal friction test.

Based on the experimental results, range analysis method was applied to the orthogonal test. As shown in Table 4, the range values (R) of the factor are as follows: lubrication > surface roughness > tool material > relation velocity > normal pressure > temperature > friction time. And fluctuations of K are also given in Fig. 2.

In order to acquire the significant factors more accurately, analysis of variance (ANOVA) method was also used. The results of ANOVA are given in Table 5, and the contribution rates of various factors are obtained and shown in Fig. 2. And then, by evaluating F values and φ_j values (contribution rate), the significant levels are acquired and described in descending order as "***", "**" and "*". Eventually, considering the results of range analysis and ANOVA comprehensively, six factors exerted great influence on the CoF, including lubrication, surface roughness, tool materials, sliding velocity, normal pressure and temperature, while friction time showed little effect on the CoF.

3.2 Effects of significant factors on CoF

All the significant factors obtained from Section 3.1, including lubrication, surface roughness, tool material, sliding velocity, normal pressure and temperature, showed great influence on the tribological behaviors. In this work, taking Cr12MoV/CP-3 and QAl10-3-1.5/CP-3 as the objects, the influencing rules of various significant factors on the CoF were also clarified and discussed.

3.2.1 Effect of lubrication

The data shown in Fig. 3 give the CoFs as a function of tool materials. As shown in Fig. 3, the CoFs

Table 3 Orthogonal table for CP-3 friction tests

No.	A, tool material	B, lubrication	C, temperature/°C	D, v/(r·min^{-1})	E, P/N	F, R_a/μm	G, t/s	μ
1	Cr12MoV	Unlubricated	25	6	100	6.3	120	0.4866
2	Cr12MoV	MoS_2	150	20	500	0.8	300	0.1430
3	Cr12MoV	Graphite	300	50	1000	0.02	600	0.1344
4	QAl10-3-1.5	Unlubricated	25	20	500	0.02	600	0.3256
5	QAl10-3-1.5	MoS_2	150	50	1000	6.3	120	0.2642
6	QAl10-3-1.5	Graphite	300	6	100	0.8	300	0.0774
7	45 steel	Unlubricated	150	6	1000	0.8	600	0.5067
8	45 steel	MoS_2	300	20	100	0.02	120	0.0766
9	45 steel	Graphite	25	50	500	6.3	300	0.3247
10	Cr12MoV	Unlubricated	300	50	500	0.8	120	0.4842
11	Cr12MoV	MoS_2	25	6	1000	0.02	300	0.1294
12	Cr12MoV	Graphite	150	20	100	6.3	600	0.1702
13	QAl10-3-1.5	Unlubricated	150	50	100	0.02	300	0.3166
14	QAl10-3-1.5	MoS_2	300	6	500	6.3	600	0.1635
15	QAl10-3-1.5	Graphite	25	20	1000	0.8	120	0.1560
16	45 steel	Unlubricated	300	20	1000	6.3	300	0.5121
17	45 steel	MoS_2	25	50	100	0.8	600	0.2539
18	45 steel	Graphite	150	6	500	0.02	120	0.0875

Table 4 Range analysis data and results

K	A	B	C	D	E	F	G
K_1	1.5478	2.6318	1.6762	1.4511	1.3813	1.9213	1.5551
K_2	1.3033	1.0306	1.4882	1.3835	1.5285	1.6212	1.5032
K_3	1.7615	0.9502	1.4482	1.7780	1.7028	1.0701	1.5543
$\overline{K}_1$	0.2580	0.4386	0.2794	0.2419	0.2302	0.3202	0.2592
$\overline{K}_2$	0.2172	0.1718	0.2480	0.2306	0.2548	0.2702	0.2505
$\overline{K}_3$	0.2936	0.1584	0.2414	0.2963	0.2838	0.1784	0.2591
R	0.0764	0.2803	0.0380	0.0658	0.0536	0.1419	0.0086

Table 5 Analysis of variance (ANOVA) of CoF

Source	SS_j	df_j	V_j	F_j	φ_j/%	Significance
A	0.0175	2	0.0088	38.09	4.3	*
B	0.2999	2	0.1499	651.94	73.3	***
C	0.0049	2	0.0025	10.74	1.7	*
D	0.0148	2	0.0074	32.25	3.2	*
E	0.0086	2	0.0043	18.76	2.1	*
F	0.0621	2	0.0311	135.06	15.1	**
G	0.0003	2	0.0001	0.64	0.24	Insignificant
$e(\mu)$	0.0007	3	0.0002		0.13	
Total	0.4088	17			100	

SS_j is sum of squares of deviation; df_j is degree of freedom; V_j is mean square; F_j is F-test value for factors; $e(\mu)$ is error

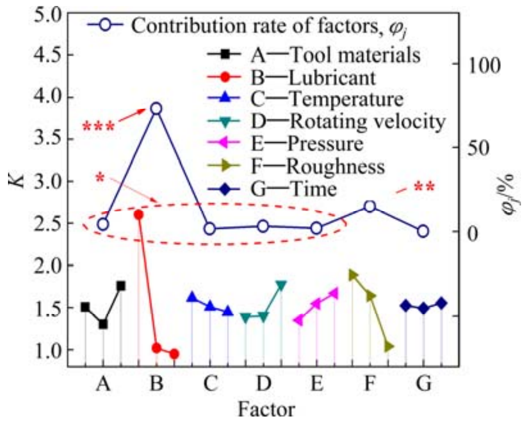

Fig. 2 Relationships between CoF and factors

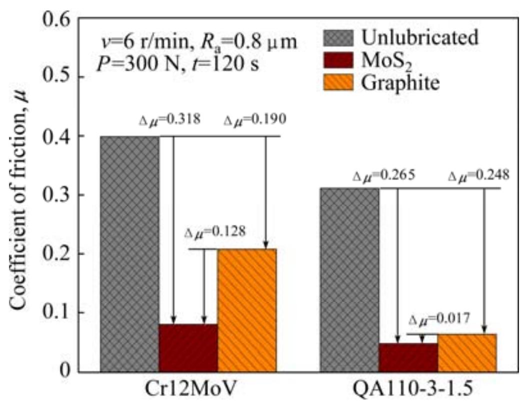

Fig. 3 CoF as function of lubricant

obtained under lubrication (MoS_2 dry film lubricated and graphite lubricated) are much smaller than those obtained under dry friction condition. Compared with the CoFs obtained under the dry friction, the CoFs of Cr12MoV/CP-3 with MoS_2 and graphite drop by 0.318 and 0.190, respectively. The improvement of friction performance is more obvious in the QAl10-3-1.5/CP-3 than that in Cr12MoV/CP-3. The results also indicate that the CoF in MoS_2 dry-film lubrication is only half of that in graphite lubrication in the Cr12MoV/CP-3. Additionally, in the QAl10-3-1.5/CP-3 tribo-pair, there is no significant difference in lubrication performance between MoS_2 dry-film and graphite lubrication.

In sheet metal forming process, the distributed lubricants became a thin smooth insulating layer between surfaces of tool and sheet, thus the direct contacts between metals were avoided and the CoF decreased accordingly [22−25]. In this work, there is a difference between graphite and MoS_2 in terms of lubrication performance. This can be explained as follows: the HCP structure of graphite gives its good lubrication properties, and the graphite usually behaves best lubrication under high speed condition in the temperature range of 200−2000 °C [23−25]. While the MoS_2, with hexagonal layered and triangular polyhedron structure, has a unique arrangement of atoms and a special interlayer spacing, thus making MoS_2 exhibit an extreme low shear strength in the parallel direction to plane and a high strength and hardness in the vertical direction [23,26]. In addition, it is more likely for MoS_2 to be transformed into a protective film with good resistance to toughness, pressure and high temperature between tools and sheet, thus making it have a very low coefficient [23,25,26].

3.2.2 Effect of tool material

The effects of tool material on the CoF are shown in Fig. 4, in which the two tool materials are compared directly under the parameters considered. Two materials are chosen for the comparison: Cr12MoV steel with high degree of hardness and QAl10-3-1.5 alloy with low hardness. As well, the sliding velocity, pressure, frictional time, temperature and surface roughness combinations are chosen for studying the effect of tool materials.

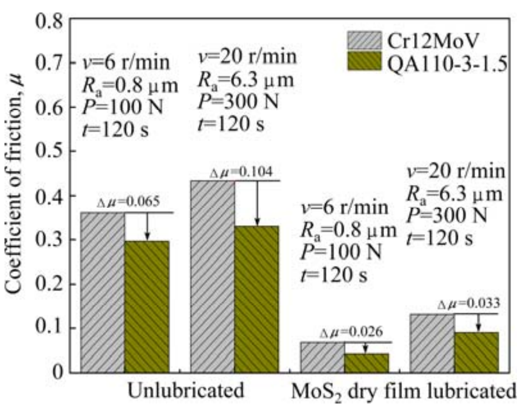

Fig. 4 CoF as function of tool material at 200 °C

It can be found that the above parameter combinations give the lowest and the highest coefficients: low velocity, low pressure and low roughness cause low CoF, while high velocity, high pressure and high roughness cause the opposite under both unlubrication and MoS_2 dry film lubrication conditions. Besides, it is evident that QAl10-3-1.5/CP-3 exhibits lower CoF than Cr12MoV/CP-3 tribo-pair. Therefore, from the perspective of tools design, QAl10-3-1.5 alloy can be chosen as sensitive tools that demand lower friction coefficient in CP-3 sheet warm forming.

3.2.3 Effect of tool roughness

Figure 5 shows the results obtained under different tool surface roughnesses and the variation of the average CoF as a function of tool roughness. As shown in Fig. 5(b), the CoFs of the two tribo-pairs increase with increasing the surface roughness. This observation agrees with that of CRISTINO et al [10], who found that the CoF changed as "S" curve with increasing the surface roughness. As well, when the roughness increases from 0.02 to 6.3 μm for two tribo-pairs, the CoF rises by more than 0.11. Comparing the curves of two tribo-pair combinations, there is a slow increase rate in the roughness range of 0.02−3.2 μm for Cr12MoV/CP-3, while the curve obtained from QAl10-3-1.5/CP-3 tends to be a straight line.

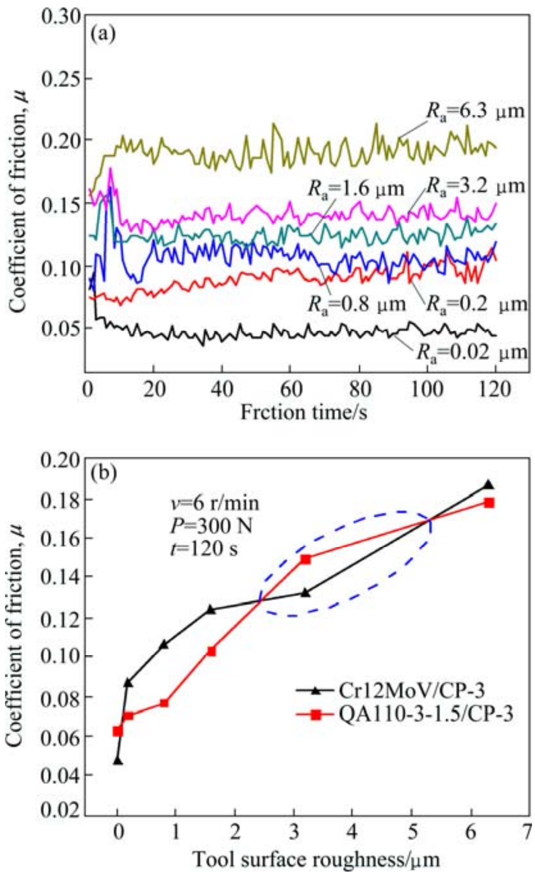

Fig. 5 CoF−friction time curve of different tool roughnesses (a) and CoF−tool roughness curve (b) of specimens at 200 °C

When the tool surface is relatively smooth, the degree of unevenness on surface is smaller, thus making a smaller CoF, because of its weak mechanical interlocking effects. However, due to the greater degree of surface unevenness, the mechanical occlusion effects are enhanced heavily when the tool surface roughness increases. As well, the local deformation and shearing of the microscopic convex portion of tool surface occur between the metal surfaces normally, which impedes the relative sliding of the two surfaces. Besides, the metal wear debris between the friction surfaces increases the frictional resistance. Therefore, considering all the above effects, the CoF is increased as the tool roughness is raised.

However, LEE et al [9] concluded that the CoF increased firstly and then decreased with increasing the surface roughness by investigating the tribological performance of steel sheets lubricated by liquid lubricants. Obviously, the results do not agree with those in this work, for its poor lubrication resulting from the less oil storage tanks on the smaller roughness surface. In this work, the solid lubricants were chosen for the tests. Therefore, the effects caused by oil storage tanks do not have significant influence on the CoF [9,27].

3.2.4 Effect of normal pressure

Figure 6 gives the CoF as a function of the normal pressure. The results show that the two tribo-pairs have the similar changing trends. The CoFs of the two tribo-pairs increase firstly and then decrease as the normal pressure is increased, and the peak value of the CoF appears at 900 N (0.04 MPa) or so. These results are similar to the data of SAHIN and WILSON [28] who indicated that when the normal pressure (p<24 MPa) was increased, the CoF of lubricated 6022-T4/A2 steel was decreased. The decreasing trend of the CoF may associate with the hardness of frictional materials. It can be found that there is at least one softer material among the combinations, such as CP-3 and QAl10-3-1.5. So, when the pressure reaches a certain value, the pressure helps to inhibit surfaces from roughening and improve the lubrication condition between tool and CP-Ti sheet, thus leading to a smaller coefficient [11,29]. However,

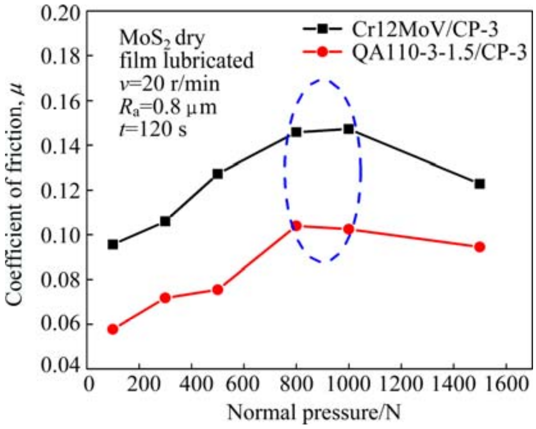

Fig. 6 CoF as function of normal pressure

when the normal pressure is under the critical pressure value, the CoF increases because the increased pressure enhances the mechanical interlocking effect between tools and sheet metal. At the same time, the lubrication quality is poorer when the pressure is not sufficient to flatten the uneven surface. Taking the two aspects of effects into consideration, there may be a special pressure interval in which the CoFs increase with increasing the normal pressure, which can also be seen in Ref. [11].

3.2.5 Effect of sliding velocity

Figure 7 shows that the two tribo-pairs have a similar tendency at different sliding velocities: lager sliding velocity results in higher CoF. And the increasing rate is closely related to the sliding velocity itself, that is to say, the CoF increases slowly at lower velocity; when the sliding velocity exceeds a certain value (about 20 r/min), the CoF increases significantly. This observation agrees with that of SAVASKAN and ALEMDAĞ [12], WANG et al [19] and TAO et al [30]. SAVASKAN and ALEMDAĞ [12] concluded that the CoF increased with increasing sliding velocity in the hydrodynamic lubrication. WAGN et al [19] explained the reason for the increase of the CoF from the atomic stratum. TAO et al [30] held that the gradually increased surface fatigue of specimen at large velocity resulted in an increased CoF, a smaller sliding velocity and a smaller fatigue resistance.

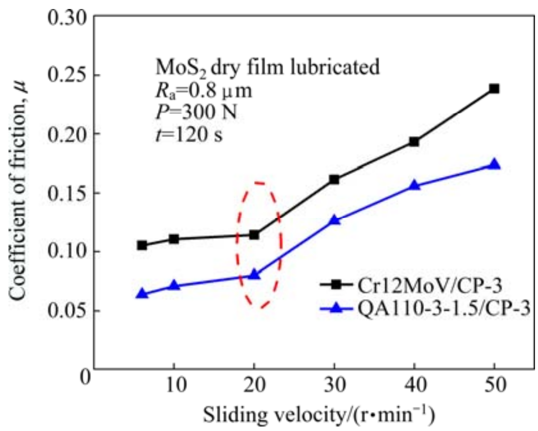

Fig. 7 CoF as function of sliding velocity

To sum up, the phenomena in Fig. 7 can be explained as follows: 1) with increasing the sliding velocity, the elastic and plastic deformation (including staggered contacts, the penetration and peeling of oxide layers) and other surface effects increase, which leads to more severe meshing contact; 2) the increased velocity weakens the molecule adhesion and extends the friction time to accumulate a variety of surface effects to hinder the relative sliding. Therefore, at low velocity, the CoF does not change significantly because the effects caused by 1) and 2) offset each other substantially; when the sliding velocity exceeds a certain value, 1) becomes the stronger effect, which makes the hindering effect greater than the promoting effect, resulting in the increase of CoF.

3.2.6 Effect of temperature

Figure 8 shows the variation of the CoF with temperature. As can be seen from the figure, with increasing the temperature, the CoF of different material combinations increases at firstly and then decreases slightly. When the temperature is lower than 100 °C, the CoF increases at a slow increasing rate with raising the temperature, while the CoF declines at a high rate in the range of 100−300 °C. This observation agrees with that of LENARD [16] who obtained the data using the aluminum sheets. Three reasons are responsible for the above phenomena: 1) at low temperatures, the elevated temperatures cause thickening of the surface oxide film of specimen and increasing adsorption force between the molecules, resulting in a slight increase in CoF; 2) when the temperature continues to rise, the oxide skins are easy to be softened and some of them peel from the surface, forming an isolation lubrication layer between the sheet metal and tools; 3) suffering from high temperatures, the tool materials become soft at a certain level so that the grinding effect between the contact points is weakened [16,17,31,32].

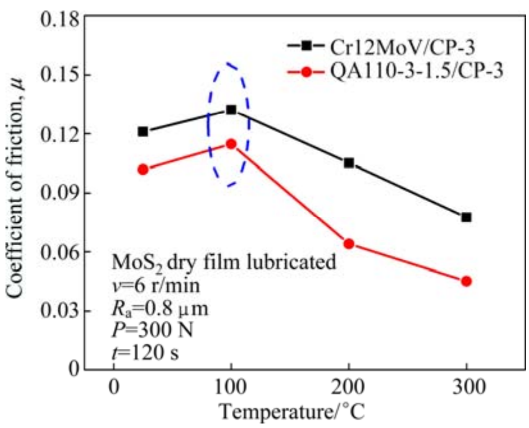

Fig. 8 CoF as function of temperature

Currently, the researches about the influence of temperature on the CoF have interested scholars in the field of sheet metal warm forming, and there have been also many different conclusions [16,17,31−34]. But, it seems that all these studies have a common characteristic that the effect of temperature on the CoF shows high sensitivity to frictional materials and the CoFs of different materials in various temperature ranges are also quite different. However, most studies show that there is always a temperature range in which the CoF reduces with increasing the temperature. The reason which causes this phenomenon still remains questionable.

The scholars seem to believe that the main reasons are concluded in two aspects. On the one hand, some changes occurred in the material itself in the wear process, including surface oxidation, wear debris, metal softening and so on [32,33]. On the other hand, the differences in CoF may be caused by the fluctuation of lubricating quality against temperature. Most of lubricants have the most suitable temperature ranges so that too high or too low temperatures can lead to poor lubrication [23].

4 Conclusions

1) Using the orthogonal design test with seven factors and three levels, the significant factors affecting the CoF in CP-3 sheet warm forming are determined as lubrication > surface roughness > tool material > sliding velocity > normal pressure > temperature.

2) Compared with the dry lubrication, both MoS_2 and graphite show a dramatic improvement in friction process at 200 °C: the maximum reductions of CoFs are 0.318 (MoS_2 lubricated) and 0.248 (graphite lubricated). And the CoFs of QAl10-3-1.5/CP-3 are smaller than those of Cr12MoV/CP-3 under the same considerations.

3) With increasing the surface roughness and the sliding velocity under MoS_2 lubrication at 200°C, the CoFs of the two tribo-pairs show a trend of increase by more than 0.11 with different rates. With increasing the normal pressure, the CoFs of two tribo-pairs with MoS_2 lubrication increase firstly and then decrease, and the CoF reaches the maximum values of 0.147 (Cr12MoV/ CP-3) and 0.103 (QAl10-3-1.5/CP-3) at 900 N.

4) With increasing the temperature under MoS_2 lubrication, the CoFs of two tribo-pairs show a modest increase from 25 to 100 °C, while the trend is reverse in the range of 100−300 °C. And the CoFs of QAl10-3-1.5/ CP-3 are lower than those of Cr12MoV/CP-3 in the whole temperature range (25−300 °C).

5) The friction and lubrication conditions in CP-Ti warm forming are affected by multi-factors. And the influencing rule of each factor is not constant and exhibits great dependence on material and process parameters, i.e., the influencing rules may be various with using different tribo-pairs and easily to be changed by the disturbance caused by process parameters.

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加热成形中纯钛板与模具间的摩擦行为

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摘 要：板料/模具间的摩擦润滑条件是影响薄壁钛合金产品成形质量、成形极限和模具寿命的关键因素。利用压缩扭转摩擦方法，结合正交试验设计，改变模具材料、润滑状态、温度和压力等参数，研究热成形 CP-3 钛板和模具间摩擦因素的变化规律及作用机理。结果表明：影响 CP-3 板料温成形摩擦因数显著因素为润滑剂、模具粗糙度、模具材料、转速、压力和温度；相对于干摩擦，石墨和 MoS_2 干膜润滑剂对板料/模具间摩擦的改善效果均很明显，摩擦因数最大降低了 0.318；不同参数下 Cr12MoV/CP-3 和铝青铜(QA110-3-1.5)/CP-3 摩擦因数的变化趋势基本相同，即随模具表面粗糙度和转速的增大而增大，随温度和压力的增加先增大然后减小。

关键词：CP-3 钛板；温成形；润滑；摩擦因数

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