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**REVIEW ARTICLE**

# Tribology in metal forming at elevated temperatures

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**Abstract:** The tribo-characteristics of metal forming at high temperatures have not yet been well understood due to the complex nature of thermal, microstructural, interaction, and process parameters. This is a review paper on the effects of temperature, coating, and lubrication to the tribological characteristics in hot forming as well as the tribometers for different metal forming processes at elevated temperatures mainly based on the experimental work. The tribological behaviors of oxides in hot forming, such as rolling and stamping, were reviewed and presented. Some commonly used surface coatings and lubricants in hot forming were given. Many types of tribometer were selected and presented and some of them provided a great potential to characterize friction and wear at elevated temperatures. Nevertheless, more testing conditions should be further investigated by developing new tribometers. Eventually, experimental results obtained from reliable tribometers could be used in theory and model developments for different forming processes and materials at high temperatures. The review also showed the great potential in further investigations and innovation in tribology.

**Keywords:** elevated temperature; hot forming; oxidation; tribometer; tribology

## 1 Introduction

Current trend in automobile industry demands lightweight components to reduce energy and material consumptions. The key areas for lightweight part production include material development (high strength steel, aluminum, magnesium, titanium, compound materials, and new alloys), part design (complex shapes and simulations), and production processes (hot forming, incremental forming, superplastic forming, and thixoforming) [1]. Generally, lightweight part manufacturing involves more sophisticated processes, materials, and product design in order to provide safety, compatibility, and durability to part structures while lowering costs [2]. Recently, low density and high strength materials have been introduced in metal forming. High strength steels (HSS) is a typical example due to their weight and crashworthiness improvements. Many research groups have been studying and improving the formability of high strength materials at high temperatures. Yanagimoto et al. [3] investigated the springback of HSS sheets by hot compression test and found that the springback was markedly reduced if the temperature was higher than 750 °C. Karbasian and Tekkaya [4] provided a review on hot stamping covering investigations on different widely used materials, finite element models, tribological and related properties as well as applications. Also, different types of tribometer were categorized to determine the friction coefficient at tool-sheet interface in hot stamping. Lin and Chen [5] reviewed experimental results and constitutive models for different metals or alloys during hot forming and divided their mechanisms and characteristics in three

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categories: phenomenological, physical-based, and artificial neutral network models.

Although the formability of high strength materials at high temperatures has been fairly well understood, there are still some remaining sources of uncertainty that should be further investigated, such as, friction, temperature, and new press technology [6]. Particularly, the tribology of metal forming at high temperatures is very much a great concern because there are several influential variables such as materials, surface coatings, lubricants, contact pressure, and temperature. The main problems occurring during hot forming processes are high friction and wear, and surface initiated fatigue. These create a great challenge to achieve high quality product and extended tool life. Recently, several research groups have carried out studies to understand friction and wear occurring in hot forming. Pelcastre et al. investigated the initiation of galling in hot sheet metal forming of Al–Si-coated ultrahigh-strength steel [7]. Kondratiuk and Kuhn evaluated the Al–Si and Zn–Ni coatings in the hot strip drawing experiments [8]. Ghiotti et al. carried out thermal and physical-simulation experiments to examine the performance of the zinc-based coating [9]. Tomala et al. tested different solid lubricants in the sliding experiments at elevated temperatures [10].

In order to understand the tribology in metal forming at elevated temperatures, the focus should be at the tool-workpiece interface. This paper provides a review of four main topics in hot forming: (1) tribological effect of oxidation at elevated temperatures, (2) tribological effect of surface coatings at elevated temperatures, (3) tribological effect of lubrication at elevated temperature, and (4) tribometers in metal forming at elevated temperatures.

## 2 Tribological effect of oxidation at elevated temperatures

The tribological behavior of oxides has been addressed in many works on rolling and hot stamping processes but only a few on forging process. Numerous literature showed the characteristics of oxides (either abrasive or lubricious) in friction contact regarding to their natures and interfacial temperatures. Literatures related to different iron oxides concluded that at high temperature (> 400 °C), hematite ($Fe_2O_3$) is very hard and abrasive, and tends to increase wear, while wüstite (FeO) and magnetite ($Fe_3O_4$) are more ductile and resistant to wear. By the 1990s, the authors estimated that high temperature wear came from a cutting effect related to shearing of micro-asperities during relative sliding between contact surfaces, and temperature involved in the phenomenon of wear by changes in the nature and properties of the contact surfaces. In this section, four main tribological considerations are reviewed: (1) tribological characteristics of oxide layers, (2) oxide in rolling process, (3) oxide in hot stamping process, and (4) formation of compacted layers (glaze layers).

### 2.1 Tribological characteristics of oxide layers

Studies on hot rolling process use the term "lubricious" to describe oxides, because they delay the abrasion of metal antagonist and tend to reduce friction. The main criteria established for oxide lubrications are [11]:

– An adhesive layer to prevent the formation of free particles oxides.

– A ductile oxide layer that accommodates plastic deformations induced by normal loads and tangential stresses.

– A sufficient layer thickness acts as a thermal insulation to its substrate. The thickness of the oxide layer depends on temperature.

– The thermal diffusivities, "$a$", of the oxide and the matrix have to be rather similar or the thermal diffusivity of the oxide has to be small compared to those of metal antagonist. If the value of "$a$" is high, the oxide layer is rapidly cooled down due to heat transfer to tools. Since it becomes hard and brittle, it produces free particles in contact leading to abrasion of the metal antagonist.

– Rapid oxidation kinetics allows healing of the oxide layer on the occurrence of microcracks and prevents micro-extrusions of very reactive metal of the underlying substrate and/or the appearance of surface defects on metal antagonist.

More recently, other criteria leading to lubrication of oxides have been identified by Aouadi et al. [12]. These criteria are:

– Crystal chemistry of lubricious oxides [13]: The authors emphasize that crystal chemistry is important in the lubrication behavior of oxides. The ionic potential of cations (ratio between the oxidation number and ionic radius) controls several physical and chemical properties of the oxide. In general, when the ionic potential is high, the extent of screening of a cation in an oxide by surrounding anions is large. Cations are then surrounded by anions but do not establish any connections between them ($ReO_3$, $V_2O_5$, etc.). Oxides with highly screened cations are generally mild in low melting point. The oxides with low ionic potential have cations that exhibit strong bonds, which are difficult for shearing (FeO, MgO, CoO, etc.). Thus, Erdemir [13] established a relationship between the ionic potentials and friction coefficient. The higher the potential, the lower the friction coefficient at high temperature.

– The softening occurs when process temperature is between 0.4 and 0.7 of the absolute melting point, which corresponds to the ductile/brittle transition of most oxides.

– The exceeding of the melting temperature of the oxide during use (similar to the mechanism that reduces friction in the liquid) but most of the usual oxides have their melting temperature above to 1,500 °C.

– The formation of a material having a layered crystal structures with weak cohesive bonds.

– Shearing in textured nano-cystalline grains is due to the result of dislocation glide.

Lubricious oxide layers are magnetite $Fe_3O_4$, spinel oxide iron-chromium $Fe(Fe_{2-x}Cr_x)O_4$, molybdenum oxide ($MoO_3$), vanadium oxide ($V_20_5$), and tungsten oxide ($WO_3$) [12]. The oxides considered as more or less abrasive are hematite ($Fe_2O_3$), molybdenum oxide ($MoO_2$), and titanium oxide (TiO and $Ti_3O_5$).

On the other hand, oxidation occuring under tribological stresses could change chemical composition and oxidation kinetics [14]. Recently, Blau et al. [15] highlighted from scratch tests that there existed a redistribution of chemical elements in the composition of materials. In fact, when a layer, for example oxide, is damaged by a scratch test, it is re-oxidized. The concentration of chemical elements changes relatively to its initial state, and a new oxide layer is then formed differently from the former. Experiment shows that re-oxidation has a more pronounced content of oxygen element. Oxidation occuring under tribological stress induced oxidation kinetics constants (Arrhenius law) is different from those obtained in the static oxidation tests. Although this has not been demonstrated, the constants are different for oxidation under static loads and under friction. This seems intuitively obvious if the ease of dissemination of oxygen ions in the joints of grains, dislocation lines and defects is taken into account.

Ilo et al. [16] offered a wear oxidized surfaces model combining the laws of Archard and Arrhenius. The authors of this review paper applied the results of this model for 1 hour at low temperature (120 °C maximum) and showed that a proper understanding of the particles movement in the contact was necessary.

### 2.2 Oxide in rolling process

Suarez et al. [17] studied the oxide layer deformation of a mild steel sheet (20 μm thick for 20 s at 1,050 °C) after rolling test. The rolling test was performed in a plane strain compression chamber, which was designed to control oxidation and obtained scales of different thicknesses (Fig. 1).

The height reductions varied between 12% and 60% at temperatures of 1,050 °C, 850 °C and 650 °C. Following the height reduction, the oxide layers were re-oxidized for 10 s at 1,050 °C. The results showed that the oxide layer thickness decreased with the reduction rate and was highly fragmented if the rolling test was conducted at a temperature below 850 °C. The extrusion of the underlying steel through the cracks had been observed. The authors concluded that the oxide layer

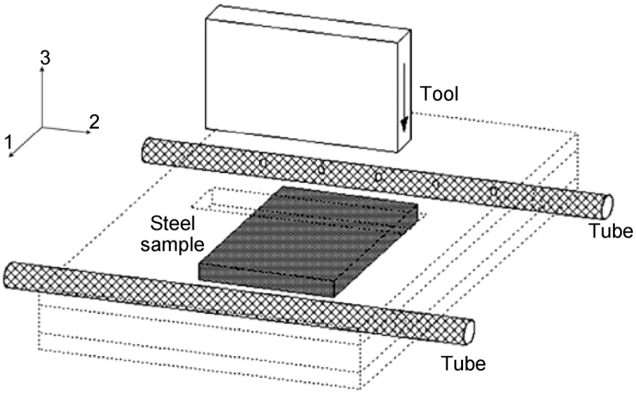

**Fig. 1** Schematic diagram of a chamber showing the positions of the steel sample, the tubes that feed gas and the upper tool. The compression direction (3) is indicated. Reproduced with permission from Ref. [17]. Copyright Elsevier, 2014.

had a plastic property above 850 °C, a ductile/brittle property between 700 °C and 850 °C, and a brittle property below 650 °C.

From the height reduction tests of mild steel sheets, Utsunomiya et al. [18] observed the micro-extrusion of matrix steel when the reduction was greater or equal to 30% at the temperature of 1,000 °C. They also noted that, at the same temperature and the height reduction less than 20%, thin layers of oxide homogeneously deformed without micro-cracking. Also, the deformation accompanied micro-cracks were found in thicker oxide layers.

The impact of the oxide layer thickness on the lubrication performance was observed in rolling tests of two stainless steel grades [19]. Similar to the previous studies, after the thickness reduction rate reached 20%, the sheets were re-oxidized at high temperature in a very short time. The 304L steel (X2CrNiMn18-09-02, austenitic stainless steel) had a generally uniform and thick oxide layer while that of the 430 steel (X4Cr16, ferritic stainless steel) was irregular and its thickness varied in a wide range. The thick oxide layer on the surface of 304L steel contributed to the lubrication of the contact. On the contrary, breaking the thin oxide layer of the 430 steel substrate caused steel/cylinder contacts, which opposed the lubricating effect of scale and induced adhesion phenomena of the ferritic stainless steel.

Picqué et al. [20] studied the effect of the micro-cracking of the iron oxide layer on mild steel extrusion, which had lower hardness than that of the scale. This extrusion phenomenon led to adhesions between the sheet and the rolls during rolling in the finishing stands. In rolling, origin of micro-cracks in the oxide scale could be derived from the growth stresses of oxide layers, or the plastic flow of the underlying metal, or the indentation of the layer by hard and adherent asperities at the cylinder surface. The authors compared four-point hot bending test results to those from a numerical model built with Forge2005 software, which simulated the flow of the oxide scale in the roll bite entry. During the tests, the oxide layer had a brittle property at 600 °C with a network of cracks perpendicular to the stress directions. Cracks were inter-granular at low strain rate ($10^{-7}$ $s^{-1}$) and became inter and intra-granular at high strain rate ($10^{-7}$ $s^{-1}$). At 700 °C and low strain rate, the oxide toughness increased and an early plastic property appeared without apparent cracking. The authors also observed that cracks appeared at the strain of 1% regardless of the temperature. At 2% strain, interfacial delamination of the oxide scale occurred and no micro-cracks were observed in the scale volume.

The evolution and influence of the roughness of the soft oxide layer of steel sheet on reduction rate is also an important research topic in rolling [19, 21]. The authors relied heavily on the numerical simulation and agreed that $R_a$ (μm) tended to decrease when the reduction ratio was increased (between 5% and 35%). However, the findings diverged somewhat with the experimental parameter "rolling speed". In all of the above studies, the authors focused preferentially on the behavior of the sheet oxide scale but some research teams looked at the tribological behavior of oxides on cylinders at high temperatures. The works of Pellizzari et al. [22–24], Vergne et al. [25] and Joos et al. [26] have been referred for many years, and the review of roll wear and oxide scale formation was presented by Zamri, in his Phd bibliography [27], and by Panjkovic [28].

The cylinder grades obtained as-cast are numerous, such as HSS, medium-speed steel (semi-HSS), high chromium steel (Cr-Steel), high chromium cast iron (HiCr), indefinite chill double pouring (ICDP), etc. The nature and the volume faction of the solidification carbides are determinative for wear resistance at high temperatures of the cylinders.

The variation of the experimental parameters (speed, load, contact geometry, test temperature, etc.) is also important. However, it should be noted that this cannot be directly achieved by rolling with height reduction tests but more or less by conventional tribological tests. It is confirmed in most of the works (often performed on a high temperature pin on disc tribometer) that friction coefficient decreases with temperature disregarding work roll grade [23, 25, 26, 29, 30]. However, there was an exception with HSS, that its friction coefficient increased in an approximately linear manner with temperature in the rolling-sliding disc on disc configuration [31]. In this case, oxides were not the same in terms of the environment and the wet conditions led to the formation of a spinel ($M_3O_4$), which could be considered as lubricious oxide, and iron oxide ($Fe_2O_3$), which was absent in the dry tests. It was surprising that the friction coefficient was higher in the wet conditions, which could be due to the differences in the real contact area between the two tests.

Pellizzari et al. [23] showed the importance of oxide layer of the antagonist C40 on wear rate of the HiCr and HSS grades, as well as the role of the compacted layers on the antagonist surface. They observed a plastic flow of oxide grains at the surface layer of the compacted layers. For HSS grades [22], there was a strong relationship between macroscopic hardness and abrasive wear resistance. However, it was not possible to discern about the relative role of the matrix and primary carbides on the wear rates of HSS, because increasing matrix microhardness was observed in correspondence of higher carbide volume percentage for the considered steels. Intermediate wear resistance between IC and HSS was shown by HiCr iron, according to its hardness.

In most cases, if the hardness is high, the wear rate is weak. This evidence was less clear for HiCr grades [23] because the wear rates were almost constant regardless of macroscopic hardness. The more ductile matrix, the HiCr grades promoted the formation of compacted layers (glaze layers) that contributed to the protection of their surfaces. With the evolution of the friction factor, interrupted tests with HiCr grades highlighted the transition between a metal/oxide contact and an oxide/oxide contact. While for HSS grades, the evolution of the friction factor was constant confirming the continuous occurrence of a metal/oxide contact.

Garza-Montes-de-Oca and Rainforth. [31] tested HSS at different temperatures in different environments (dry and wet conditions) on a rolling–sliding disc on disc configuration (Fig. 2).

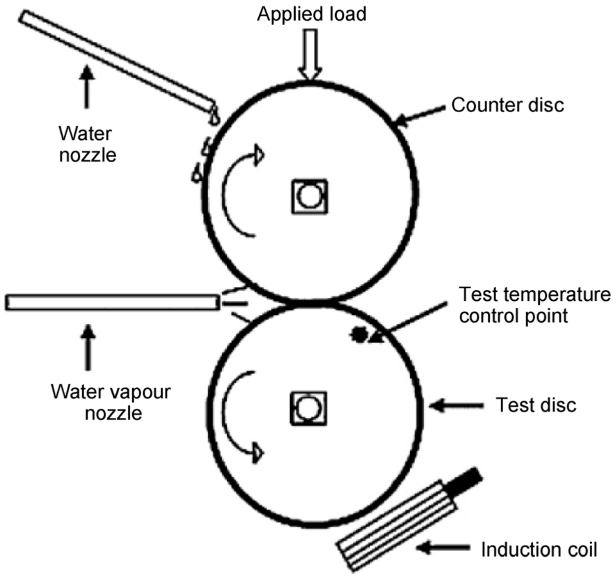

**Fig. 2** Schematic representation of the rig used for the rolling–sliding experiments. Reproduced with permission from Ref. [31]. Copyright Elsevier, 2014.

The specific wear rate of the HSS steel discs was greater for the tests conducted in dry air compared to the tests with the presence of water in the range of 400–600 ℃. The specific wear rates of the dry tests were strongly temperature dependent, while those in the wet tests were temperature independent. All of the worn surfaces contained oxides and wear particles were almost entirely oxide in the water lubricated tests, while a mixture of oxide and metal was found in the dry tests. The dry tests exhibited a combination of metallic ploughing and oxidational wear, while for the wet tests, the wear mechanism was essentially oxidational at all temperatures.

For an overview, the main wear mechanisms of work rolls (Table 1) and more precisely HSS work roll (Table 2) are a combination of abrasion and oxidation. Meanwhile, abrasion could be understood as plastic deformation of the matrix.

**Table 1** The general modes or wear mechanisms of work rolls [27].

| Authors | Type of mills | Roll wear modes |
|---|---|---|
| Nakagawa et al. (1982); Lundberg (1993) | High chromium iron roll | Thermal, mechanical fatigues and abrasion |
| Colas et al. (1999) | High-speed-steel rolls | Consider oxidation as one of the mechanisms besides thermal and mechanical fatigue |
| Boccalini and Sinatora (2002); Garza-Montes-de-Oca and Rainforth (2009) | High-speed-steel rolls | At least abrasion, oxidation and thermal fatigue |

**Table 2** The general modes or wear mechanims of HSS work roll [27].

| Authors | Mechanisms of HSS work roll | Justification |
|---|---|---|
| Pellizzari et al. (2005) | Combination of abrasion and oxidation | Based on typical topography of the worn surface (abrasion) and SEM observations of oxide (oxidation) |
| Pellizzari et al. (2009) | Abrasion, triboxiation and adhesion. However, abrasion is a dominant mechanism. | Based on observation on the roll track and XRD analysis |
| Garza-Montes-de-Oca and Rainforth (2009) | (1) Dry condition: a mixture of oxidational and plastic deformation<br>(2) Wet condition: oxidation | Based on level of oxidation of the surface; oxide is mechanically mixed into metal surface and XRD diffraction |
| Joos et al. (2007) | Abrasion | Based on the formation of oxide debris, SEM observations and the coefficient of friction |

### 2.3 Oxide in hot stamping process

In automotive industry, there is a strong relationship between cost reduction and HSS performances:

(1) Increase of crash performance and safety,

(2) reduction of fuel consumption and environmental impact, and

(3) increase of accuracy and precision for easy, cheap and reliable joining and assembly.

With regards to these aspects, the introduction of HSS to car structures is one of the solutions to increase the strength-to-mass ratio of sheet components. The steel grade 22MnB5 with or without Al–Si coating is one of the standard HSS sheets. High mechanical performances are performed directly by hot forming processes. Some research teams studied the formability of the 22MnB5 steel [32, 33]. Wear and friction behaviors of 22MnB5 steel sliding against steel tools during hot stamping process were studied in numerous literatures [34−40].

Hardell et al. [34, 35] studied the wear behavior of high strength boron steel (HSS or UHSS) at elevated temperatures with the reciprocating pin on disc test machine. The nitrided tool steel pins had a spherical end. Both uncoated and coated high strength boron steel discs were tested. The coated discs were coated with 25 μm Al–Si. The test temperatures were from 40 °C to 800 °C. The normal load was 20 N for the high temperature tests and 50 N for the tests at 40 °C. The stroke lengths were 1 mm and 2 mm, the frequency was 50 Hz, and the test durations were 15 min and 20 min. At the beginning of the contact, the friction coefficients were very high for both treated and untreated tool steel. With nitrided pins, the friction coefficient decreased with sliding distance and temperature, and the evolution was quite different from the untreated pins because of the increased friction coefficient. At high temperature, plasma nitriding of the tool steel pins was effective in providing protection against severe adhesive wear (seizure or galling). The Al–Si coating on boron steel was effective in reducing friction during rubbing against plasma nitrided tool at 800 °C but resulted in significantly higher friction at 500 °C. The wear characteristic of the tool steel was temperature dependent. At low temperature (40 °C), the tool steel wear was low but increased at higher temperature (400 °C). At 800 °C, wear changes of plasma nitrided tool steels occurred, which were small and the wear on the Al–Si-coated high-strength steel was significantly lower. The principal material removal mechanism appeared to be adhesive wear at all temperatures coupled with the contributions from abrading action of oxidized wear debris at elevated temperatures. With temperature, the decrease of the coefficients of friction was probably due to the formation of oxides and/or intermetallic compounds, which consequently reduced adhesion.

The same research team [36] developed a phenomenological model to explain the galling mechanisms encountered during interaction between an uncoated tool steel and Al–Si coated UHSS. The authors noted the formation of compacted oxidized wear debris for the development of glaze layers, which significantly reduced the occurrence of galling. The damage of the oxide layer was associated with the high roughness of the tool.

Boher et al. [38−40] studied coated 22MnB5 sheet in contact with three steel grades on the hot stamping simulator device. Glaze layers, resulting from Al–Si coated sheet compacted particles, were observed on the tool surface and dependent on the micro-structural steel grades. In addition, plastic deformation of the steel grades, under frictional stresses, was one of the main tool steel wear mechanisms. Ghiotti et al. confirmed similar results [37]. The worn pin surface analysis by SEM/EDX and 3D profilometer showed that both adhesive and abrasive wear mechanisms took place. The adhesion could be attributed to the aluminum transfer from the sheet protective Al–Si coating, whereas the formation of oxide particles acting as wear debris could support the occurrence of abrasive wear.

### 2.4 Formation of compacted layers (glaze layers)

By the 2010s, the authors were convinced that formation of compacted layers at contact surface [41] significantly reduced the occurrence of galling [36] and modified friction conditions. These compacted layers were named tribo-layers [42, 43] or glaze layers [44–47].

The formation of compacted layers, "glaze layers" (an important phenomenon in the accommodation of the contact surfaces), is exclusively induced by friction and more particularly by the friction at high temperatures. The glaze layers are the result of the circulation of free particles in the contact that adhere totally or partially on one or two surfaces in contact, and this can occur regardless of the ambient temperature of the contact. The glaze layers consist of either fragmented metallic particles, which are completely oxidized in the contact, or partially oxidized metallic particles (either oxides from the fragmentation of the oxide layers or a mixture of these particles). These particles, initially free, are compacted to form the glaze layer, which has a smooth roughness [42]. The development of a glaze layer would imply multiple simultaneous stages: the production of particles, agglomeration and sintering, as well as the evolution in the contact.

Inman et al. [46] identified two main types of wear that could occur (severe wear and mild wear) associated with the presence or absence of the glaze layer. The difference between severe wear and mild wear would result from the establishment of the glaze layer.

In high temperature friction during tribological tests associated with the studies on rolling [24], forging [48], and hot stamping [36], it was often shown that the development of layers at the interface of two materials contributed to the reduction of friction and wear rate. The stability of the friction factor was often associated with the transition of metal/metal contact (or metal/oxide) to an oxide/oxide contact.

## 3 Tribological effect of surface coatings at elevated temperatures

In hot metal forming, wear or damage normally occurs at the tool-workpiece interface, which could be caused by galling (material transfer), mechanical loads, thermal fatigue, oxidation, plastic deformation, and cracking. As a result, the surfaces of tool and workpiece are normally treated with different coatings to provide resistance to wear, fatigue, and oxidation. Many research groups have carried out studies in determining the tribological characteristics of different surface coatings in hot metal forming. However, only the work of some selected research groups are presented here.

For tool materials, the heat treatment must be optimized to acquire high thermal fatigue resistance because of the cyclic temperatures and mechanical loads. Sjöström and Bergström studied the microstructural condition of the martensitic chromium hot-work tool steel alloy and found out that the thermal fatigue crack was dependent on the heat treatment and the thermal fatigue resistance was dependent on the test temperatures [49]. Persson et al. investigated the surface cracking resistance of different surface engineering processes and concluded that the resistance against thermal crack of the surface engineered tool steels were dependent on the substrate materials [50]. Tsubouchi et al. developed a tool surface coating by welding a Co-based matrix powder mixed with NbC powder using plasma transferred arc welding for hot stainless steel rolling [51]. Although the results showed that galling was reduced but the tool life was short. Podgornik and Hogmark compared different surface modification techniques (polishing, plasma nitriding, and diamond-like carbon (DLC) coating) on cold work tool steel against stainless steel [52]. The authors found out that surface roughness highly influenced galling and suggested that polishing was important to reduce material transfer. DLC coating also provided low friction at high loads but offered competitive results to fine polishing. If the tool surface was polished after treatment, plasma nitriding was also able to provide high wear resistance. Hard TiN coatings did not improve tool galling properties when in contact with stainless steel. Rodríguez-Baracaldo et al. used the ball-on-disc test to investigate the load capacity of physical vapor deposition (PVD) $(Ti_{0.7}Al_{0.3})N$ coating on gas nitride AISI H13 steel and the results showed that the duplex coating system provided higher load capacity than the single-layered system did [53]. Özgür et al. tested five different PVD film coatings (TiN, TiAlN, CrN, AlTiN and TiCN) on M41 steel to investigate their thermal diffusivities and wear performance [54]. This research group suggested that TiAlN and AlTiN were appropriate for tools under thermal loads. Polcar et al. examined the wear resistance performance of CrN and multilayered Cr/CrN coatings using the pin-on-disc test in the temperature range 600–800 °C and the results showed that Cr/CrN multilayers provided higher wear resistance than CrN did [55]. Hardell and Prakash observed the wear behavior of TiAlN and CrN coatings against ball bearing steel at 400 °C and found out that TiAlN performed better than CrN [56].

For sheet materials, surface coatings are normally applied to remove oxide scale and decarburization occurring during the heating. Al–Si coating is usually applied on high strength steel sheets to eliminate such problem. Hardell et al. investigated the tribological characteristics of Al–Si coated high strength steel against different tool steels at temperatures up to 800 °C [7, 34–36, 56]. This research group observed that Al–Si coating reduced friction at elevated temperatures. They also observed that wear were dependent on temperature and adhesive wear was the principal mechanism at elevated temperatures. Kondratiuk and Kuhn analyzed the wear behavior of Al–Si and Zn–Ni coatings in the hot strip drawing experiments [8]. The results showed that Zn–Ni coating gave lower friction coefficients than Al–Si did due to the ZnO formation.

## 4 Tribological effect of lubricants at elevated temperatures

At elevated temperatures, typical lubricants cannot operate due to the complex tribological conditions. As a result, hot forming applications generally have limited usage of lubricants. Nevertheless, some research works that used lubricants at elevated temperatures are reviewed here.

Li et al. investigated the lubrication behavior of graphite by using the ring compression tests of Ti-6Al-4V alloy in the temperature range of 750–1,000 °C [57]. The results showed that graphite improved the friction coefficient. However, the friction coefficient increased with increasing temperature under lubricated conditions. Matsumoto and Osakada used the ring compression test and sliding test of different coated tools in the temperature range of 200–300 °C to investigate the friction behavior of different lubricants (mineral oil, alcohol, ester, phosphor EP, sulfur EP, and $MoS_2$ [58]. The authors found that thin alcohol lubricant reduce friction significantly. Daouben et al. studied the effects of film thickness and particle sizes of graphite based lubricant by using the warm hot upsetting sliding test (WHUST) at 1,100 °C [59]. The authors concluded that the film thickness in the flash zone and particle size affected the friction and wear behavior. Buchner et al. examined the tribological performance of four aluminum forging (graphite-based) lubricants by using the rotational forging tribometer in the temperature range of 250–450 °C [60]. Each lubricant provided ranges of friction coefficient under different conditions, which one could select to fit certain condition. Tomala et al. investigated three commercially available lubricants (functional solid lubricants and inorganic, water dilutable binders) by using the sliding tests at temperatures up to 800 °C [10]. The results showed that effective lubricants could be selected based on the friction coefficient, tool-workpiece adhesion, abrasive wear of tool surface, and tool life. Yanagida and Azushima used the hot flat drawing test to evaluate the friction behavior of two lubricants (water base white type and water base white type with solid lubricant) in the temperature range of 600–800 °C [61]. The results showed that both lubricants reduced friction coefficient and were effective for decreasing stamping load and die wear.

## 5 Tribometers in metal forming at elevated temperatures

There have been many literature reviews related to tribometers in metal forming. Dohda et al. published several literature reviews on tribological characteristics evaluation in metal forming [62–65]. These publications reflected the history of tribometers development but most of them were utilized in metal forming and processes carried out at room temperature. Munther and Lenard found that the temperature, velocity, load, and geometry affected the friction, heat transfer, and wear of the hot flat rolling of steels [66]. Beynon summarized four key issues in the tribology of hot metal forming: friction, heat transfer, lubrication, wear, and fatigue [67]. Groche and Callies also stressed that changing the sheet material greatly affected the entire tribological system, particularly the tool material and lubrication [68]. Mori et al. observed the influence of localized heating of shearing zone in the punching of ultra-high strength steel sheet on punch load and tool life [69]. Groche et al. differentiated tribometers under different loading conditions, for instances, pin-on-disc test, ring compression test and double cup extrusion [70, 71].

Despite the fact that there are many tribometers for cold metal forming, the tribometers for hot metal forming are considerably few. In this paper, a review of current tribometers for hot metal forming is presented. The principles, conditions, materials and key results of the tribometers are described and discussed. Four topics of tribometers at high temperatures are considered: (1) tribometers for sheet metal forming, (2) tribometers for bulk metal forming, (3) tribometer for rolling, and (4) discussions on high temperature tribometers.

### 5.1 Tribometers for sheet metal forming

Pin-on-disc tests are commonly used to observe friction and wear between rigid friction pairs. The principle of the pin-on-disc test is demonstrated in Fig. 3 [72]. The ball or pin is positioned perpendicular to the disc. Either the pin or the disc is driven to revolve about the disc center, creating a wear track. Wear on the pin and the disc can be observed and friction coefficient between the pin and the disc can be determined.

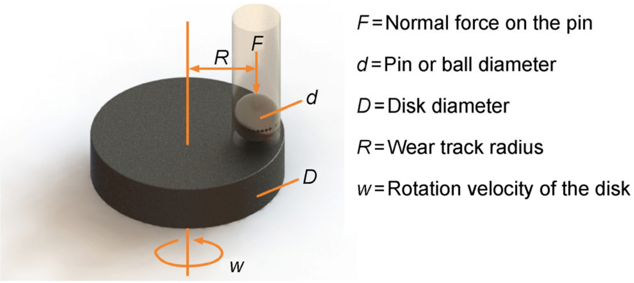

**Fig. 3** Schematic of pin-on-disc wear test system.

Vergne et al. attempted to correlate the evolution of friction coefficient with the appearance, the nature, and the mechanical properties of the scales formed on hot metal working tools and their products by using the high temperature pin-on-disc tribometer at 950 °C [25]. The results showed that the evolution of friction coefficient could be divided up to different stages depending on the oxide scale at different temperatures as shown in Fig. 4. It could be concluded from the results that two friction regimes were observed: (1) low friction variation due to the formed oxide scale on the pin before sliding and (2) large friction variation due to the growth of oxide scale on the pin during sliding.

Marzouki et al. studied the effectiveness of different tool coatings in hot drawing by using the pin-on-disc test at 400 °C and the results showed that coatings reduced friction but increased adhesive wear as shown in Fig. 5 [73]. The authors also concluded that the cast iron/uncoated sheet pair was not suitable for application at high temperature.

Hardell et al. investigated the friction and wear of high strength boron steel at high temperatures up to 800 °C by using the SRV test and the results showed that friction was reduced with increasing temperature as shown in Fig. 6 [34, 35]. The decreasing friction with increasing temperature could be due to the formation of compacted layers of oxide and wear debris at high temperatures.

Ghiotti et al. examined the friction between the blanks and the dies by using the pin-on-disc testing

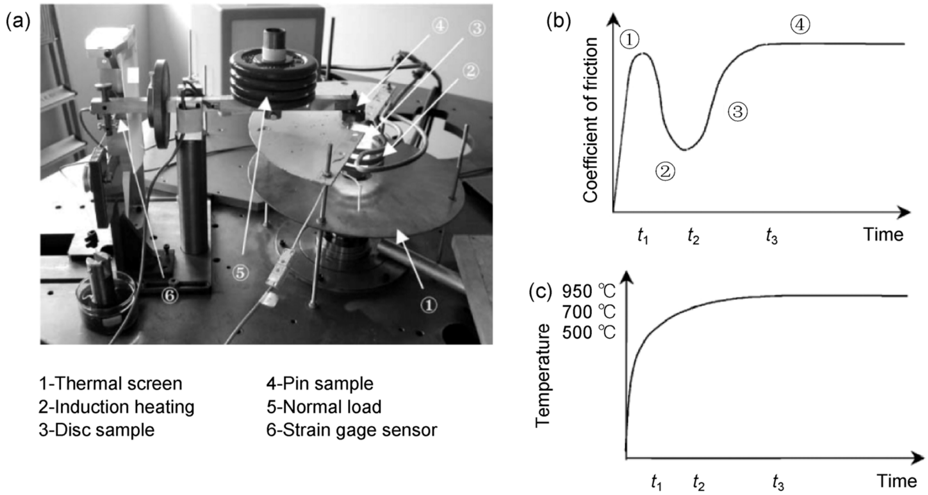

**Fig. 4** (a) High temperature pin-on-disc tribometer; (b) evolution of friction coefficient in the case of the non stabilized temperature in the pin; (c) evolution of the superficial temperature of the pin calculated by a numerical model. Reproduced with permission from Ref. [25]. Copyright Elsevier, 2014.

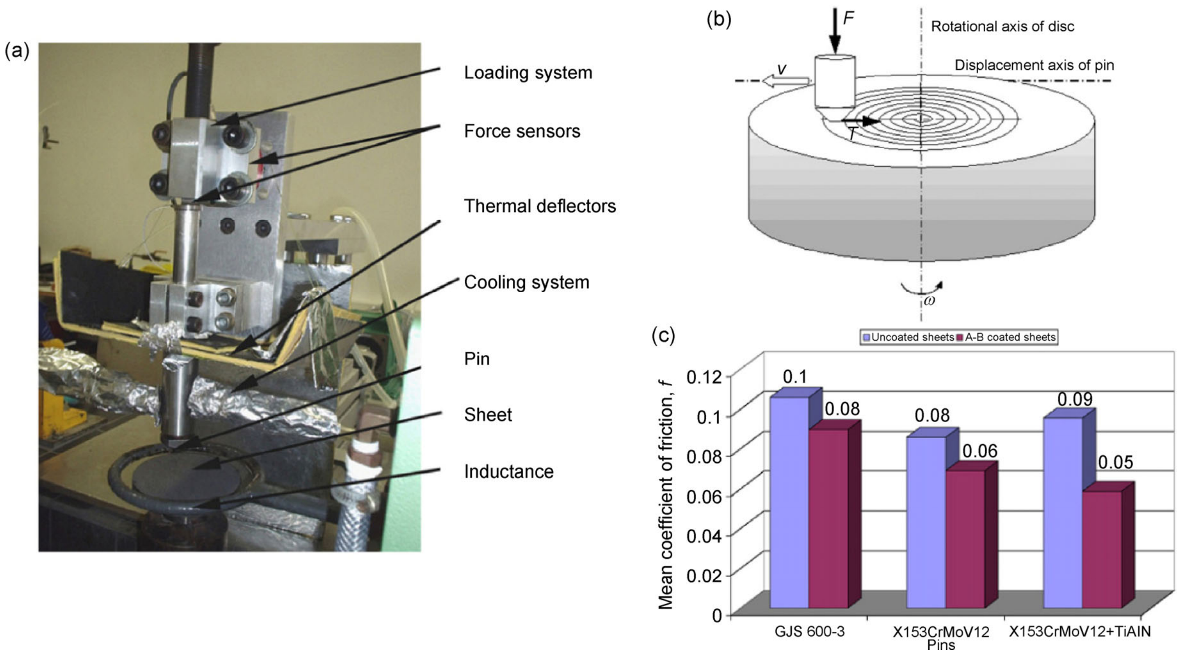

**Fig. 5** (a) Tribometer at high temperature in open contact; (b) pin-on-disc test; (c) mean coefficients of friction after tests at 400 °C. Reproduced with permission from Ref. [73]. Copyright Elsevier, 2014.

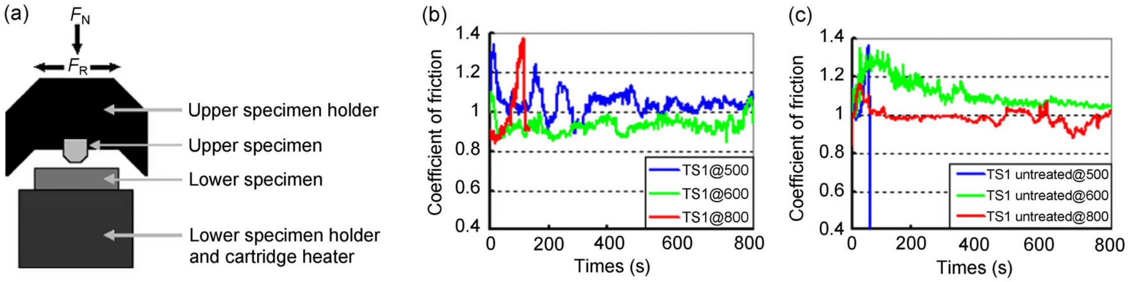

**Fig. 6** (a) SRV test configuration; (b) coefficient of friction vs. time of plasma nitride tool steel 1 and boron steel pair; (c) coefficient of friction vs. time of untreated tool steel 1 and boron steel pair (load: 20 N; stroke 2 mm; frequency: 50 Hz). Reproduced with permission from Ref. [34]. Copyright Elsevier, 2014.

apparatus (Fig. 7) equipped with a high temperature chamber (500–800 °C). The results showed that the friction coefficient decreased with temperature at low contact pressure (5 MPa) and with contact pressure at low temperature (500 °C) [74]. The elaboration of the pin-on-disc test was further described in Ref. [37]. The authors concluded that the blank/disc temperature and contact pressure highly influenced the friction coefficient.

Zhu et al. used the pin-on-disc test to study the contact behavior of the oxide scale in the roll bite during hot rolling (900 °C) and observed that the wear mechanism of the pin surface could be divided into three stages as shown in Fig. 8 [75]. At stage I, a thin oxide scale formed on the pin reduced friction. At stage II, the growth of oxide scale increased friction. At stage III, the oxide scale reached a critical value and wear debris were generated.

Hanna studied the tribological behaviors of aluminum 5083 and magnesium AZ31B sheets during sliding against AISI P20 tools at high temperature of 450 °C by using the flat-on-flat test method as shown in Fig. 9(a) [76]. The flat steel block was loaded and driven to oscillate along the flat sheet. The coefficient of friction results demonstrated that this measurement method was useful to observe the possible formation of chemical films from lubricants, and breakdown of non-conducting layers and coatings or the buildup of oxides during sliding as seen in Fig. 9(b).

Several researchers have developed a strip drawing apparatus to measure friction and wear in sheet metal forming at high temperatures and some of the strip drawing tests are presented here. Yanagida et al. developed the flat strip drawing test to examine friction coefficient at high temperatures in hot stamping as shown in Fig. 10 [77]. The strip was drawn by the tension device and loaded by the compression device. Then, the friction coefficient was calculated by the measured tension and compression loads. The strip material was SPHC (0.15% C–0.6% Mn) steel and the

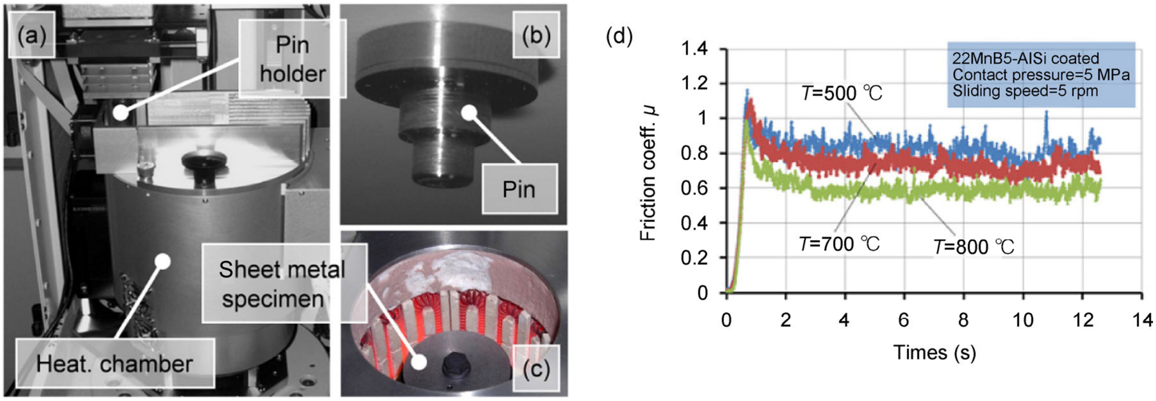

**Fig. 7** High temperature pin-on-disc apparatus: (a) overall experimental setup; (b) pin; (c) disc in the chamber; (d) friction coefficient vs. time at different temperatures. Reproduced with permission from Ref. [74]. Copyright Elsevier, 2014.

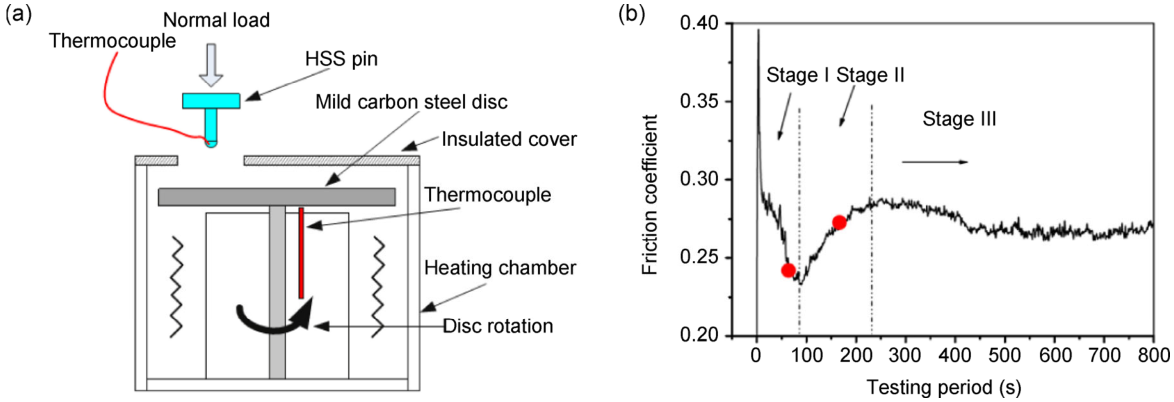

**Fig. 8** (a) Schematic of high temperature pin-on-disc test configuration; (b) three tribological stages and two interrupted points. Reproduced with permission from Ref. [75]. Copyright Elsevier, 2014.

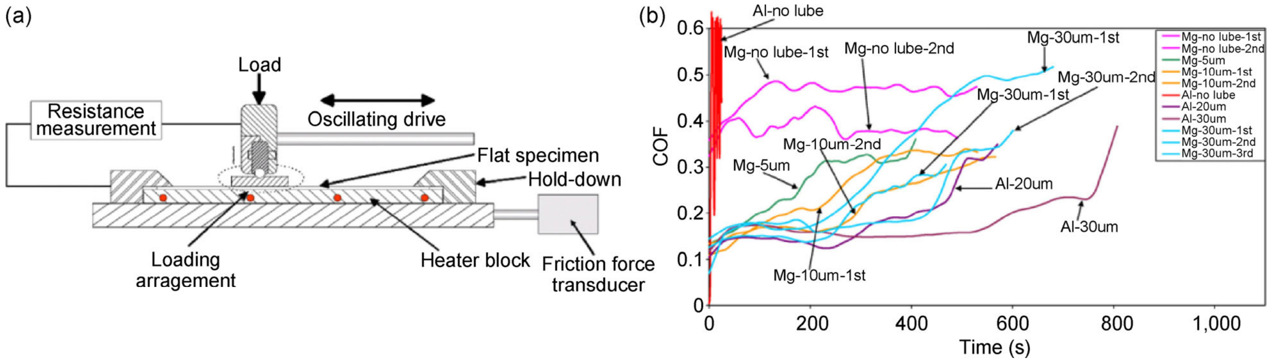

**Fig. 9** (a) Schematic drawing showing the reciprocating tribo- test machine; (b) friction coefficient results of Al 5083 and Mg AZ31B with lubrication for sheet at 450 ℃, 50 N load and 0.11 Hz sliding speed with different BN lube thickness. Reproduced with permission from Ref. [76]. Copyright Elsevier, 2014.

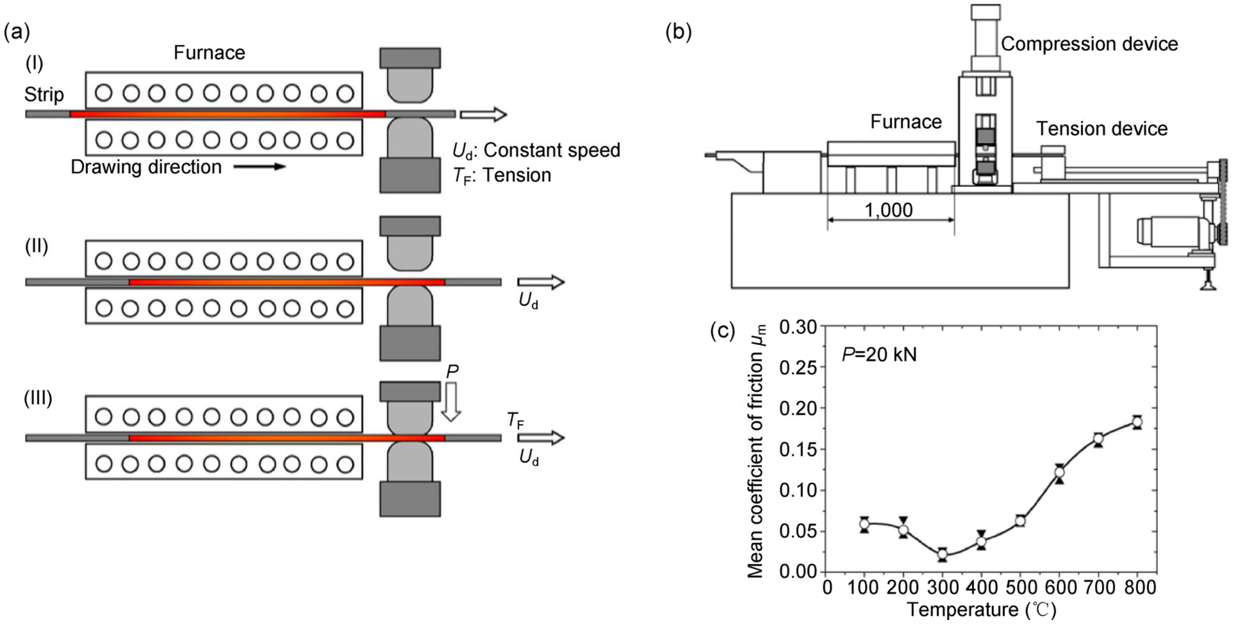

**Fig. 10** (a) Schematic representation of hot flat strip drawing test; (b) schematic representation of hot flat strip drawing test machine; (c) effect of temperature on coefficient of friction. Reproduced with permission from Ref. [77]. Copyright Elsevier, 2014.

die material was SDK61. The results showed that the friction coefficient decreased with increasing temperature up to 300 ℃ and increased with increasing temperature above 300 ℃. The decreasing friction coefficient with temperature was due to melting of the silicate type inorganic compound and the increasing coefficient of friction with temperature was due to the reduced effect of the additives. This flat strip drawing test provided a direct measurement of friction coefficient in hot stamping.

Kondratiuk and Kuhn investigated the tribological characteristics of Al–Si coating and electro-plated Zn–Ni coating of boron steel sheets by using the hot strip drawing simulator as shown in Fig. 11 [8]. The strip was heated and transferred to the drawing area. The strip was then compressed by the tool holders and drawn by the holding device. The measured compression and drawing forces were used to calculate the friction coefficient. The sheet material was 22MnB5 with different coatings and the tool material was eroded of hardened 1.2379 steel. The testing temperature was 880 ℃. The results showed that Zn–Ni coating provided lower friction coefficients, which could be due to the oxidized top layer of the zinc based coating.

Boher et al. examined wear damage of the tool radius at high temperatures by using the deep-drawing process simulator as shown in Fig. 12 [39]. The wear behavior of three different tool steels pre-alloyed Al–Si

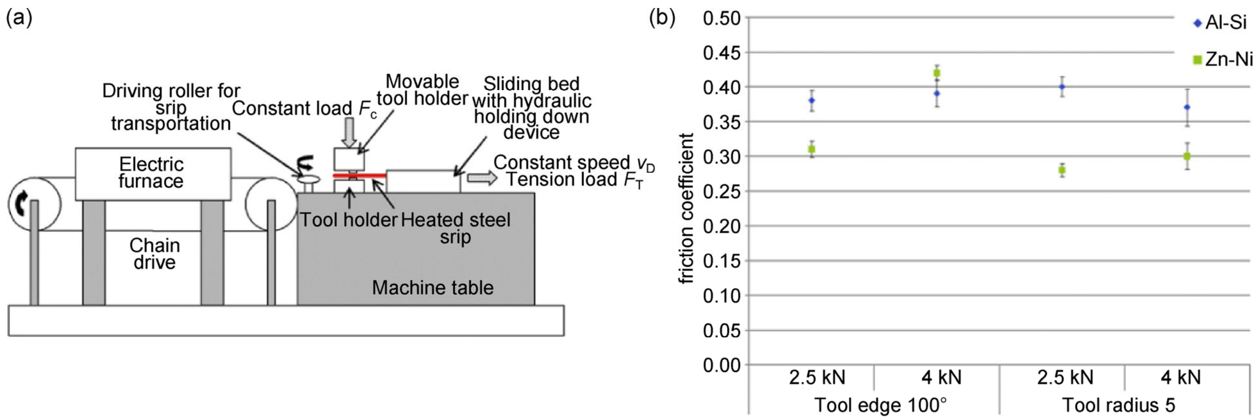

**Fig. 11** (a) Schematic representation of hot flat strip drawing simulator; (b) coefficients of friction for Al–Si and Zn–Ni coatings at different tested conditions in comparison. Reproduced with permission from Ref. [8]. Copyright Elsevier, 2014.

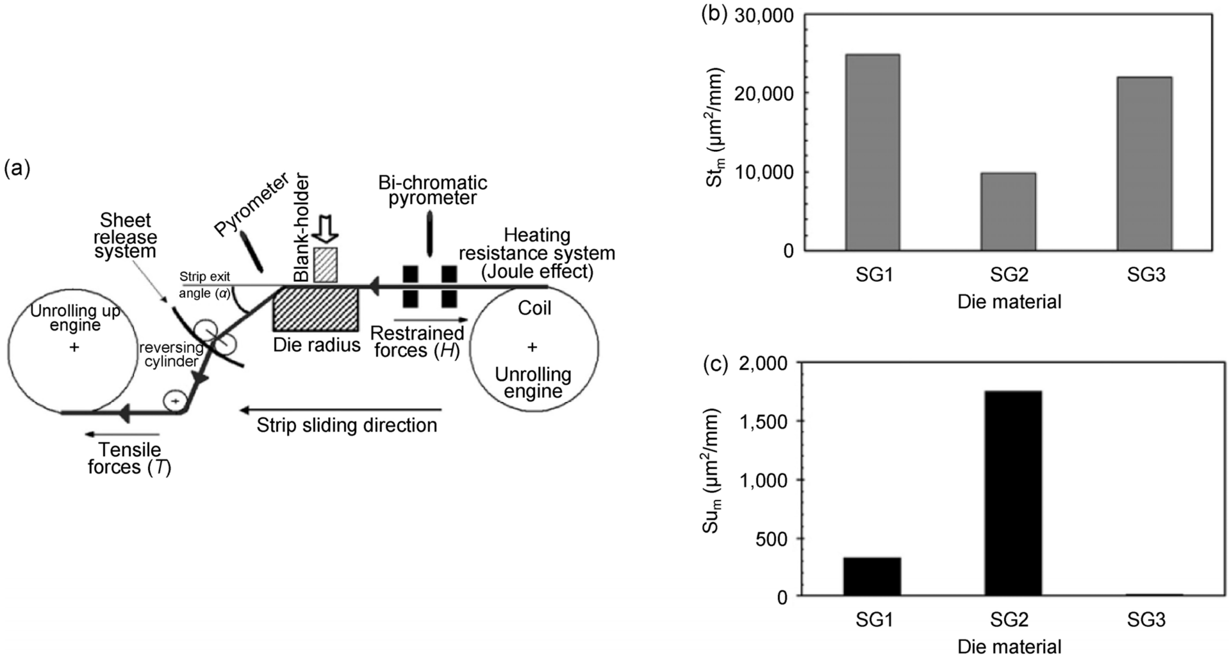

**Fig. 12** (a) Diagram of the deep-drawing process simulator (DDPS); ranking of the three steel grades regarding their propensity to adhesion and abrasion, evaluated respectively by (b) the transfer damage criterion and (c) the material loss criterion after 5,000 cycles. Reproduced with permission from Ref. [39]. Copyright Elsevier, 2015.

press-hardened high-strength steel (Usibor 1500P®) was investigated. During the test, the strip temperature was controlled by the Bi-chromatic pyrometer to achieve 875 °C. After the temperature was reached, the strip was slid on the die radius under normal loading and pulled through by the rolling up engine. After many cycles of sliding, the cross-section of the die was observed by scanning electron microscope (SEM) to observe the damage and by energy dispersive spectroscopy (EDS) to observe the chemical composition of the wear elements. The authors concluded that the modification of the formulation of tool materials could improve their adhesion and abrasion resistance in the investigated condition.

There have also been several research groups developing bending under tension apparatus to measure the tribological characteristics of sheet metal forming. Dohda et al. developed a U-Bending-Ironing tribometer (Fig. 13) to investigate the tribological phenomenon of magnesium sheets formed by tools

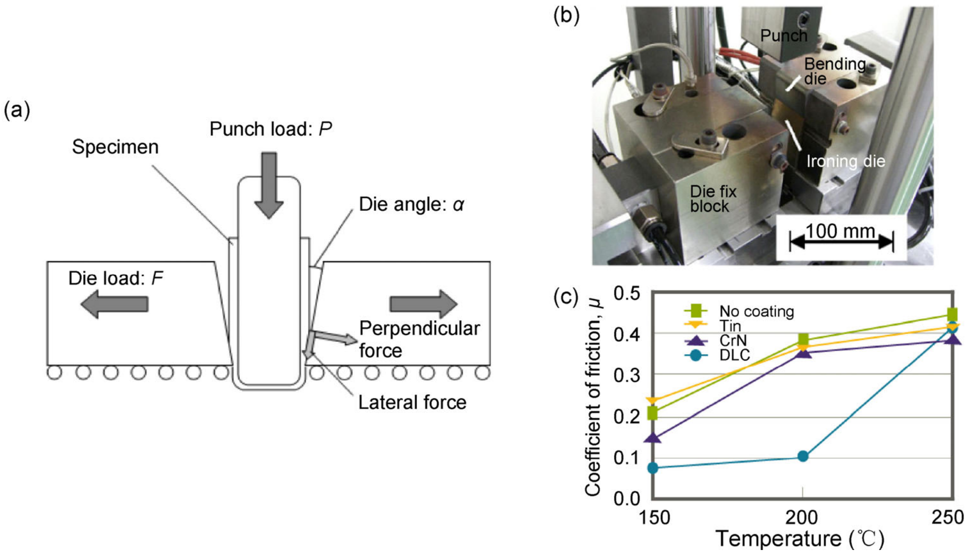

**Fig. 13** (a) Schematic of the U-bending-ironing tribometer; (b) U-bending-ironing apparatus; (c) friction coefficient of different coatings at different temperatures. Reproduced with permission from Ref. [78].

having different coatings at high temperatures [78]. The results showed tool coated with DLC provided the lowest friction coefficients. The authors also observed that the variation of friction coefficient with temperature was affected by the deformational resistance.

A bending under tension test can be seen as a tensile test on strip material with the additional local bending. Gali et al. developed the hot forming friction measurement setup as shown in Fig. 14 [79]. According to the figure, a strip was placed around the rotating heater (25–250 ℃) and pulled on both ends by the tensile force. The strip was also compressed by the steel pin, which had an embedded load cell to measure the normal load. The friction coefficients were calculated from the measured tensile and normal forces. The pin material was P20 steel and the strip material was AA5083 aluminum alloy. During the experiment, boron nitride was also applied on the strip surface. The results showed that friction coefficients increased with temperature due to the effects of abrasion at low temperature and softening tribolayer at high temperature.

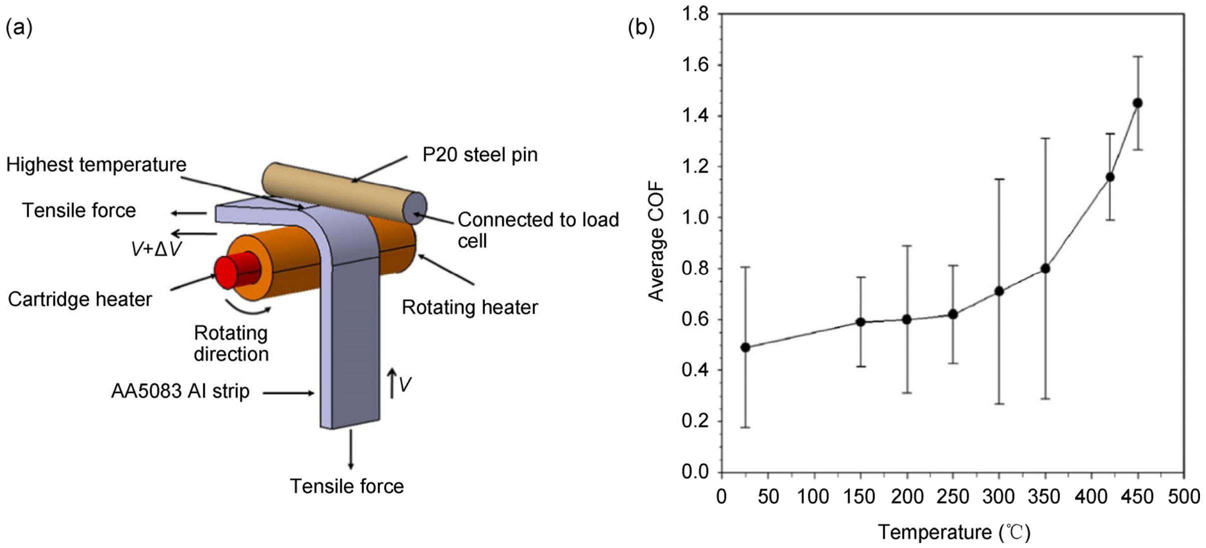

**Fig. 14** (a) Schematic of the bending under tension test; (b) average COF vs. temperature plot for AA5083 alloy. Reproduced with permission from Ref. [79]. Copyright Elsevier, 2014.

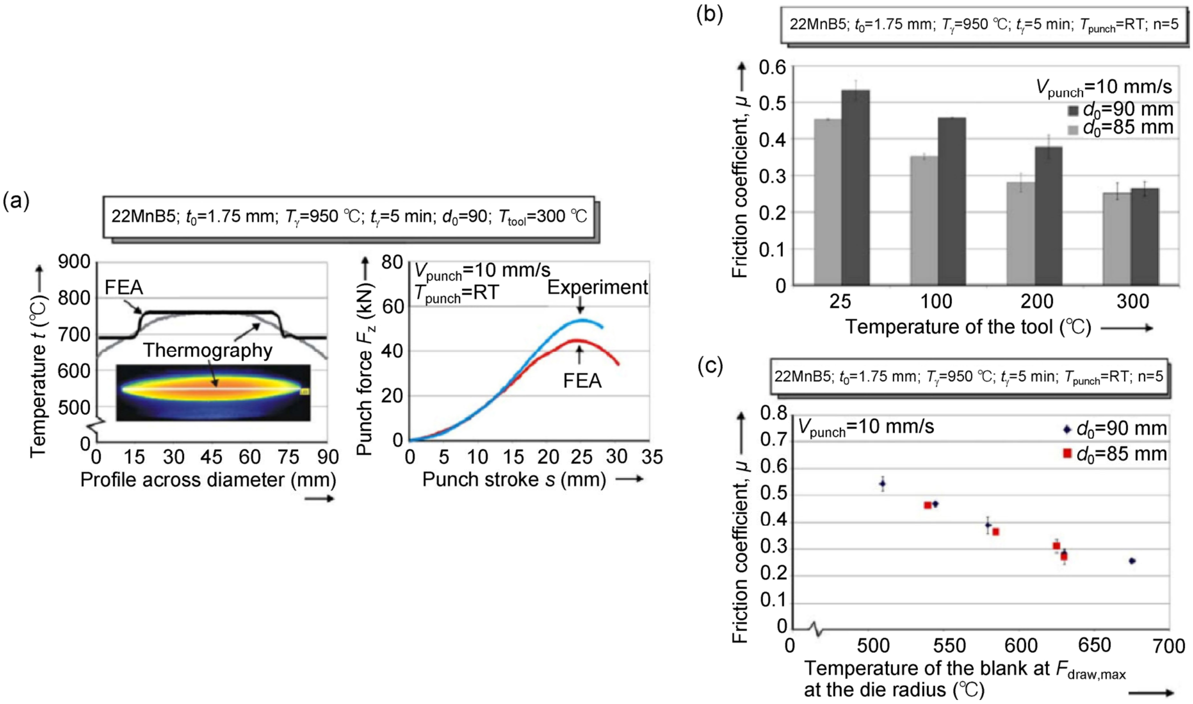

**Fig. 15** (a) Comparison between measured and via FEA predicted data regarding the temperature profile across the blank diameter instantaneous before the drawing operation (left) and the evolution of the drawing force as function of the punch stroke (right); (b) evolution of the friction coefficient in dependency of the tool temperature during the temperature of the punch remains at room temperature; (c) friction coefficient as function of the blank temperature in the contact area at the die radius at the moment of the maximum drawing force. Reproduced with permission from Ref. [80]. Copyright Springer, 2015.

A combination of experimental, analytical, and numerical methods can also be used to investigate the tribological characteristics of sheet metal forming at high temperatures. Geiger et al. determined the friction coefficients in hot sheet metal forming (500–650 ℃) by using the experimental-analytical-numerical method [80]. The experimental evaluation was carried out by the cup deep drawing test. Meanwhile, the Siebel's model was used as the analytical evaluation to obtain friction coefficient and the finite element (FE) simulation was utilized to evaluate the forming process. The results showed that increasing temperature of Al/Si precoated steel 22MnB5 improved tribological conditions in hot stamping. The authors also observed that the friction coefficient was influenced by the blank temperature.

Based on the mentioned tribometers for sheet metal forming at high temperatures, a summary of friction coefficients under various working conditions obtained from these tribometers is described in Table 3.

### 5.2 Tribometers for bulk metal forming

Traditionally, it is very difficult to measure the friction coefficient for forging process. The friction forces are usually evaluated by studying the punching force. Ceron et al. developed a tribometer to measure the friction coefficient for forging where a rotating punch was punched into the workpiece and the friction coefficient was then determined by the rotation torque as shown in Fig. 16 [81].

Wang et al. provided a review of friction testing techniques for aluminum extrusion processes and categorized the techniques into three types: field or process tests; extrusion friction tests; and tribological tests [82]. Groche et al. reviewed general friction test stands for bulk metal forming and summarized them into seven types: ring compression test, double cup extrusion; spike test; pin-on-disc test; Wanheim bay tribometer; upsetting sliding test; and sliding compression test [70, 71].

**Table 3** Coefficients of friction under various conditions obtained from different tribo-testing methods for sheet metal forming at high temperatures

| Types | Authors | Material pairs | Lubrication | Temperatures | COF |
|---|---|---|---|---|---|
| Pin-on-disc test | Vergne et al. (2001) | Cast iron/AISI 1018 mild steel | Dry | Room | 0.60–0.70 |
| | | | | 950 ˚C | 0.40–0.50 |
| | Marzouki et al. (2007) | GJS 600-3/Uncoated steel | Dry | 400 ˚C | 0.10 |
| | | GJS 600-3/Coated steel | Dry | 400 ˚C | 0.08 |
| | | X153CrMoV12/Uncoated steel | Dry | 400 ˚C | 0.08 |
| | | X153CrMoV12/Coated steel | Dry | 400 ˚C | 0.06 |
| | | X153CrMoV12+TiAlN/Uncoated steel | Dry | 400 ˚C | 0.09 |
| | | X153CrMoV12+TiAlN/Coated steel | Dry | 400 ˚C | 0.05 |
| | Hardell et al. (2008) | Plasma nitrided tool steel/Boron steel | Dry | 500 ˚C | 1.00–1.30 |
| | | Plasma nitrided tool steel/Boron steel | Dry | 600 ˚C | 0.90–1.10 |
| | | Plasma nitrided tool steel/Boron steel | Dry | 800 ˚C | 0.85–0.95 |
| | | Untreated tool steel/Boron steel | Dry | 500 ˚C | 1.00–1.39 |
| | | Untreated tool steel/Boron steel | Dry | 600 ˚C | 0.97–1.35 |
| | | Untreated tool steel/Boron steel | Dry | 800 ˚C | 0.81–1.19 |
| | Ghiotti et al. (2011) | Tool steel/22MnB5+Al–Si coating | Dry | 500 ˚C | 0.80 |
| | | Tool steel/22MnB5+Al–Si coating | Dry | 700 ˚C | 0.75 |
| | | Tool steel/22MnB5+Al–Si coating | Dry | 800 ˚C | 0.60 |
| | Zhu et al. (2013) | High speed steel/Strip steel | Dry | 900 ˚C | 0.26–0.28 |
| Flat-on-flat test | Hanna (2009) | Tool steel/AA5083 | Boron nitride | 450 ˚C | 0.10–0.30 |
| | | Tool steel/AZ31B | Boron nitride | 450 ˚C | 0.10–0.50 |
| Strip drawing test | Yanagida et al. (2010) | SPHC steel/SKD61 | Dry | 100 ˚C | 0.06 |
| | | SPHC steel/SKD61 | Dry | 200 ˚C | 0.05 |
| | | SPHC steel/SKD61 | Dry | 300 ˚C | 0.02 |
| | | SPHC steel/SKD61 | Dry | 400 ˚C | 0.04 |
| | | SPHC steel/SKD61 | Dry | 500 ˚C | 0.07 |
| | | SPHC steel/SKD61 | Dry | 600 ˚C | 0.12 |
| | | SPHC steel/SKD61 | Dry | 700 ˚C | 0.17 |
| | | SPHC steel/SKD61 | Dry | 800 ˚C | 0.18 |
| | Kondratiuk et al. (2011) | 1.2379 steel/22MnB5+Al–Si coating | Dry | 880 ˚C | 0.36–0.40 |
| | | 1.2379 steel/22MnB5+Zn–Ni coating | Dry | 880 ˚C | 0.28–0.43 |
| | Boher et al. (2012) | Tool steel/Usibor1500P® | Dry | 875 ˚C | N/A |
| Bending under tension test | Dohda et al. (2009) | Tool (No coating)/Magnesium | Dry | 150–250 ˚C | 0.22–0.42 |
| | | Tool (TiN)/Magnesium | Dry | 150–250 ˚C | 0.21–0.41 |
| | | Tool (CrN)/Magnesium | Dry | 150–250 ˚C | 0.15–0.39 |
| | | Tool (DLC)/Magnesium | Dry | 150–250 ˚C | 0.08–0.41 |
| | Gali et al. (2013) | P20 steel/AA5083 | Boron nitride | 25–250 ˚C | 0.41–0.62 |
| | | P20 steel/AA5083 | Boron nitride | 300–450 ˚C | 0.71–1.45 |
| Experimental-analytical-numerical method | Geiger et al. (2008) | Tool steel/22MnB5+Al–Si coating | Dry | 500 ˚C | 0.53 |
| | | Tool steel/22MnB5+Al–Si coating | Dry | 540 ˚C | 0.46 |
| | | Tool steel/22MnB5+Al–Si coating | Dry | 580 ˚C | 0.39 |
| | | Tool steel/22MnB5+Al–Si coating | Dry | 620 ˚C | 0.30 |

Ball-on-disc test is also commonly used to study the tribological characteristics of bulk metal forming at high temperatures. Figure 17 displays the schematic diagram of the ball-on-disc test [83]. The ball is rigidly mounted and driven to oscillate across the surface of the flat specimen. Friction and temperature can be measured in order to observe the tribological effects.

Wang et al. used the ball-on-disc test (Fig. 18) to investigate the effect of temperature (25–450 ˚C) on friction coefficient of 7475 aluminum alloy against

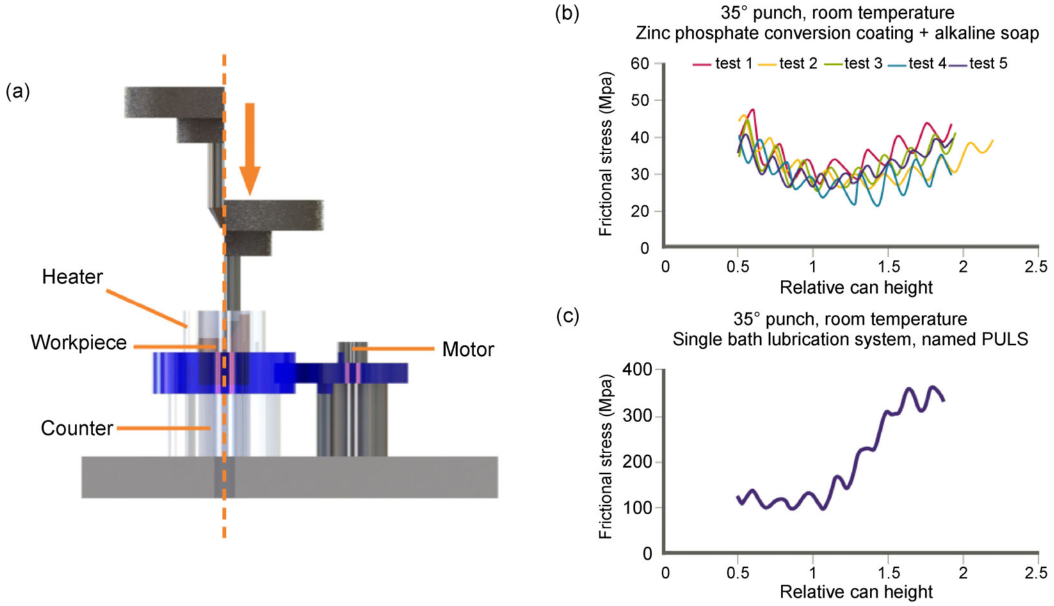

**Fig. 16** (a) Schematic of the tribometer for forging; (b) and (c) are experimental results of different lubricants. Reproduced with permission from Ref. [81].

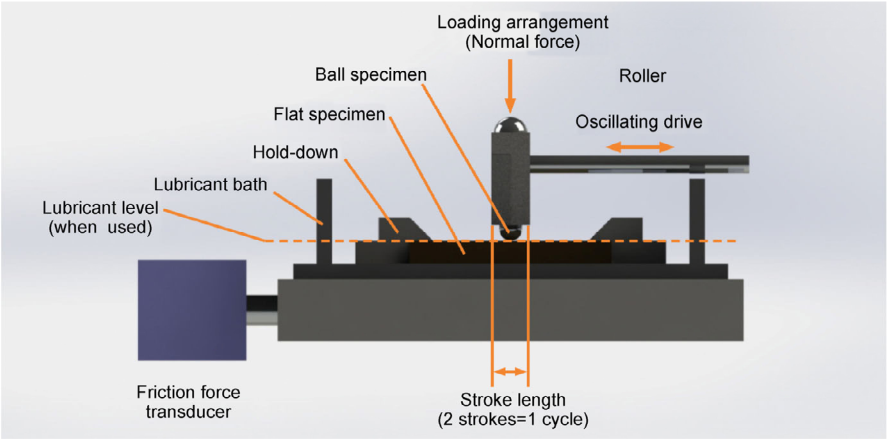

**Fig. 17** Schematic of ball-on-disc wear test system.

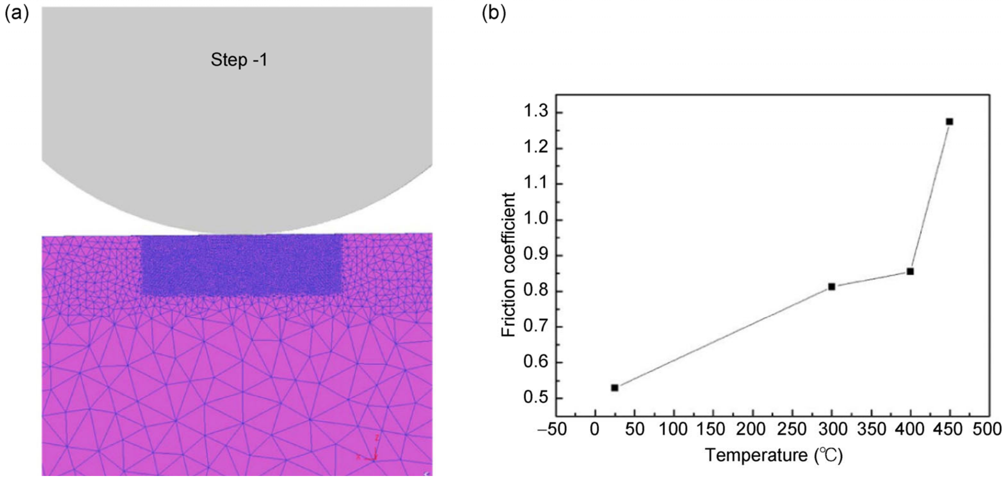

**Fig. 18** (a) FE model of the contact in the ball-on-disc tests; (b) variation of the mean friction coefficient with temperature. Reproduced with permission from Ref. [84]. Copyright Elsevier, 2014.

steel and found out that friction coefficient increased with temperature due to the changes of strain and stress states around the contact point, generating wear particles [84]. They also observed that plowing friction might have contributed to the great friction coefficient values.

A block-on-disc test is also used to evaluate the friction and wear behavior of bulk metal forming at high temperatures. Pellizzari examined the surface engineered tool steel for aluminum extrusion dies in order to understand and obtain optimal tribological properties for hot aluminum extrusion (250–350 °C) [85]. He used the block-on-disc test to evaluate the tribological properties as shown in Fig. 19(a). The material of the tool steel (representing extrusion die) was AISI H11 and different surface coatings were applied to the steel blocks. The disc (representing billet) was aluminum alloy AA 6082. The test was carried out in air using a load of 40 N and a sliding speed of 0.1 ms$^{-1}$. The results shown in Fig. 19(b) demonstrates that two friction regimes existed: minor fluctuations (regime Ⅰ) and large fluctuations (regime Ⅱ). Pellizzari also found that coatings helped improve friction and wear of the steel blocks. In addition, the samples with compound layer performed better than those with the diffusion layer only and the improved surface finishing also positively influenced the accumulation of Al on the die surface.

Another method used to study the friction and wear behavior of bulk metal forming at high temperatures is the block-on-cylinder test. Björk et al. developed the block-on-cylinder test to investigate the tribological effects of die coating (nitriding and chemical vapor deposition (CVD) coating by TiC + TiN) in hot extrusion (620 °C), as shown in Fig. 20 [86]. The results showed that the CVD coating provided better wear performance than the nitride steel. Moreover, the CVD TiC + TiN coated steel dies were worn by abrasion at the inlet of the bearing.

A ring compression test is normally carried out to determine friction coefficients in bulk metal forming at high temperatures. Li et al. investigated the

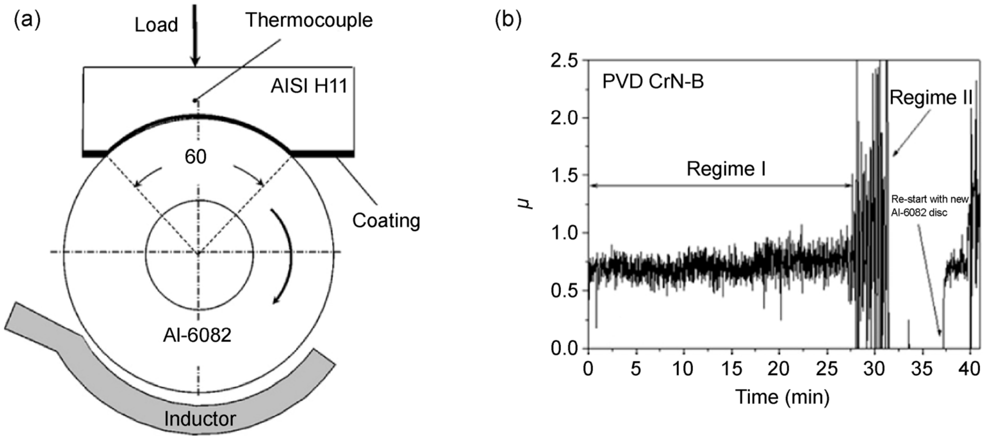

**Fig. 19** (a) Block-on-disc test; (b) diagram of friction coefficient during the test. Reproduced with permission from Ref. [85]. Copyright Elsevier, 2014.

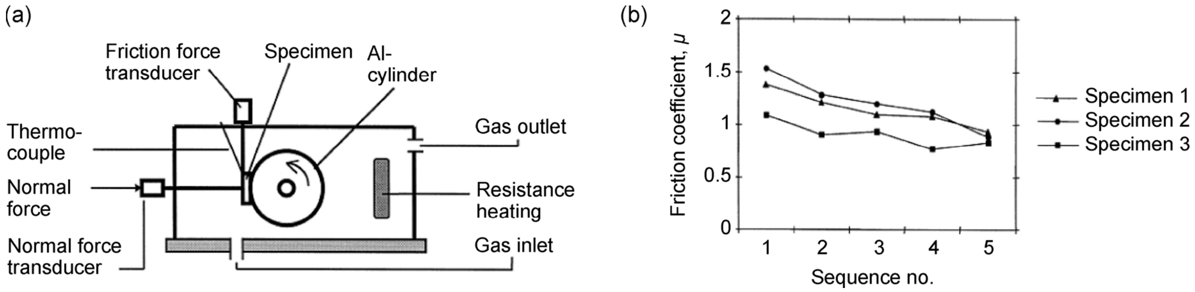

**Fig. 20** (a) Block-on-disc test; (b) diagram of friction coefficient during the test. Reproduced with permission from Ref. [86]. Copyright Elsevier, 2014.

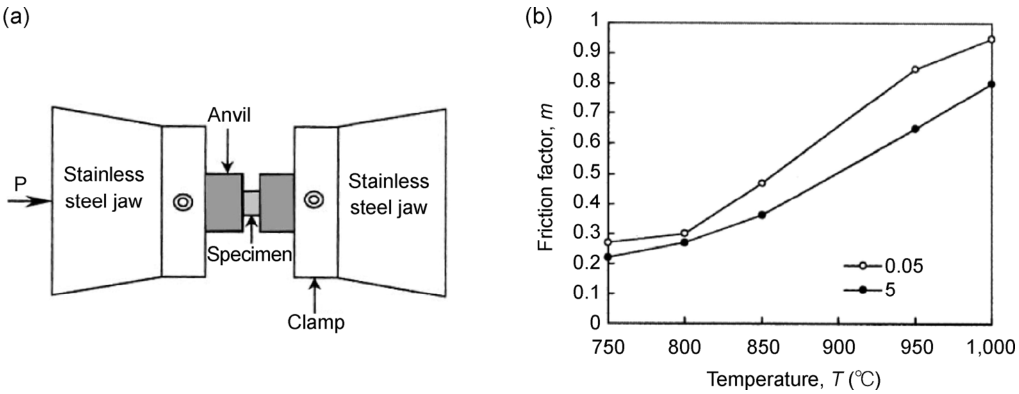

**Fig. 21** (a) Schematic drawing of the ring compression test; (b) dependence of friction factor on the temperature. Reproduced with permission from Ref. [57]. Copyright Elsevier, 2014.

lubrication behavior of graphite by using the ring compression test as shown in Fig. 21 [57]. The specimen was a 5 mm thick Ti-6Al-4V alloy ring with 15 mm and 7.5 mm outer and inner diameters, respectively. The tests were carried out at constant strain rates from 0.05 to 15 $s^{-1}$ and temperatures from 750 °C to 1,000 °C. The results showed that the friction factor increased with temperature and decreased with strain rate. Furthermore, graphite powder dispersed in engine oil could be used effectively as lubricant for compression tests below 800 °C.

Matsumoto and Osada utilized the ring compression test to evaluate the friction behaviors of the selected lubricants and coatings used in warm forging (200 °C) of magnesium alloy ZK60 against WC tool [58]. According to the results, alcohol and sulfur EP lubricants provided superior performance than the others and DLC coating caused a low friction.

A sliding test was also utilized to evaluate the friction behaviors in bulk metal forming at high temperatures. Peterson et al. used the reciprocating test apparatus to study the nature of oxide friction of high temperature alloys (up to 700 °C) and found out that the film friction for rhenates, tungstates and molydates were similar, which could be dominated by oxygen [87]. They also concluded that the friction was independent of the substrate materials. Matsumoto and Osada utilized the spiral sliding tests to evaluate the friction behaviors of the selected lubricants and coatings used in warm forging (100 °C) of magnesium alloy ZK60 against WC tool as shown in Fig. 22. From the results, the existence of oxide layer on the billet surface caused

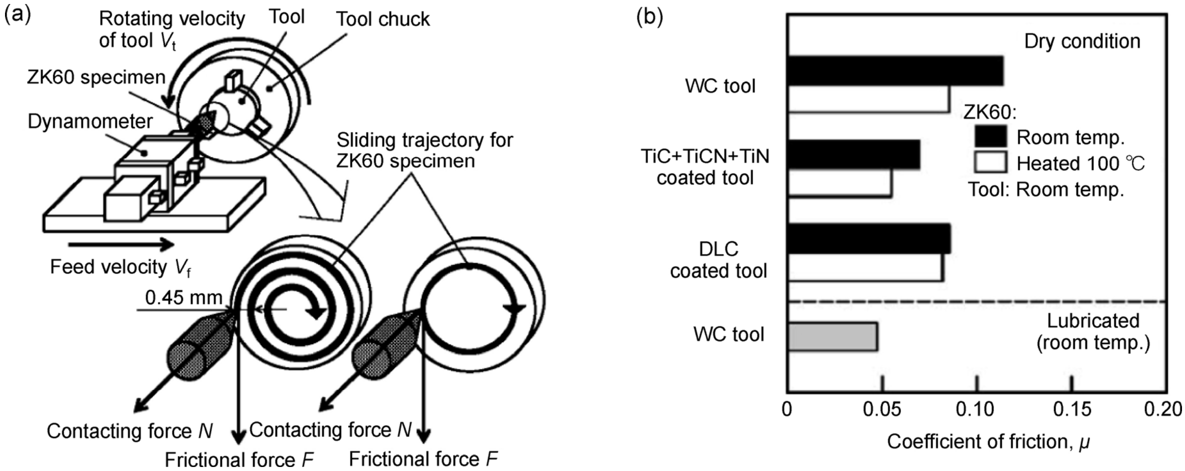

**Fig. 22** (a) Schematic of spiral sliding test on lathe; (b) coefficient of friction of magnesium alloy sliding spirally on surfaces of WC and coated tools. Reproduced with permission from Ref. [58]. Copyright Elsevier, 2014.

the increase of friction and DLC coating provided low friction and adhesion. As a result, it was recommended that the billet should be kept in non-oxidizing atmosphere to remove the oxide from the billet before forging [58].

Mosaddegh et al. measured the friction coefficient of steel-steel and steel-NBK7 pairs at 577 °C by using the modified sliding test as seen in Fig. 23 [88]. It was found that the viscoelastic properties of glass influenced the stick-slip response above the glass transition temperature.

An upsetting-sliding test can also be used to investigate tribological characteristics of bulk metal forming at high temperatures. Daouben et al. developed the warm hot upsetting sliding test (WHUST) that simulated hot forging conditions having contact pressure, sliding velocity, contactor sliding velocity, and contactor and specimen temperatures as shown in Fig. 24 [59]. Those factors were similar to the industrial conditions. By using WHUST, this research group investigated the effects of graphite based lubricant film thickness and particle sizes on friction and wear of nitride tool steel at 1,100 °C. In addition, they found that the structure of the graphite layer influenced the efficiency of the lubricant film.

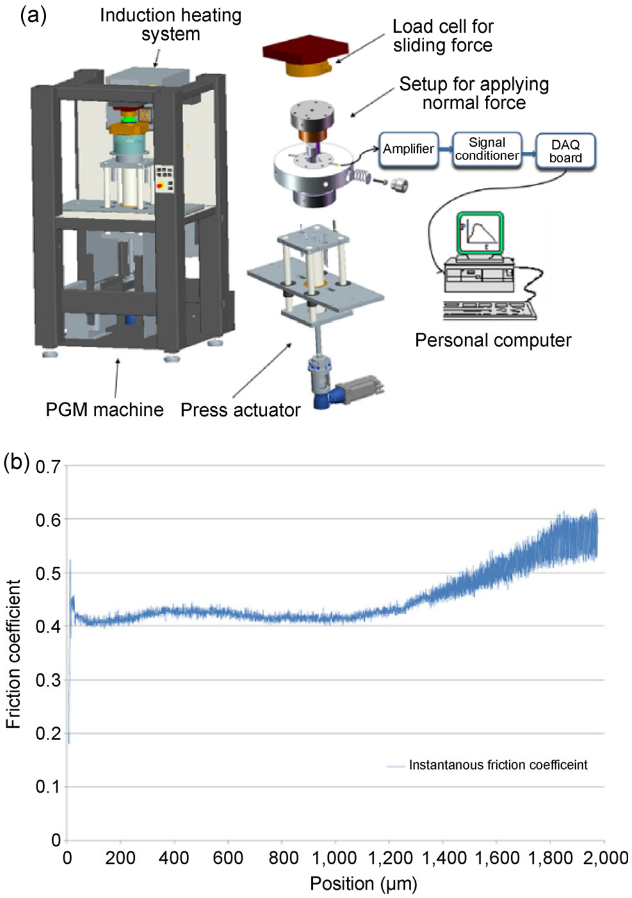

**Fig. 23** (a) Experimental setup of the modified sliding test; (b) instantaneous friction coefficient curve between a pair of steel–steel at 577 °C. Reproduced with permission from Ref. [88]. Copyright Elsevier, 2014.

A rotational forging test can also be used to evaluate the tribological properties of lubricants in hot forging. Buchner et al. evaluated the behaviors of different lubricants used in hot forging (250–450 °C) of aluminum by using the rotational forging test as shown in Fig. 25 [60]. In this test, the specimen was mounted on a rotary disc, compressed by the tool, and the frictional torque was measured. The results showed that clear formations of lubricant groups were observed, which could be applied to chosen process parameters and materials.

A non-contact test has also been developed by Saiki et al. to evaluate the tribological properties of aluminum in hot forging by ultrasonic examination. The schematic of the experimental setup is in Fig. 26 [89]. In the experiment, the workpiece was mounted in the lower die, which was heated up to 300 °C. The ultrasonic probe was embedded in the upper die for measurements at the contact interface between the upper die and workpiece through the reflection intensity of ultrasonic waves. According to the results of the ultrasonic tests, lubrication caused the contact pressure to decrease and changed the contact interface of the workpiece and die.

Based on the mentioned tribometers for bulk metal forming at high temperatures, a summary of friction coefficients under various working conditions obtained from these tribometers is tabulated in Table 4.

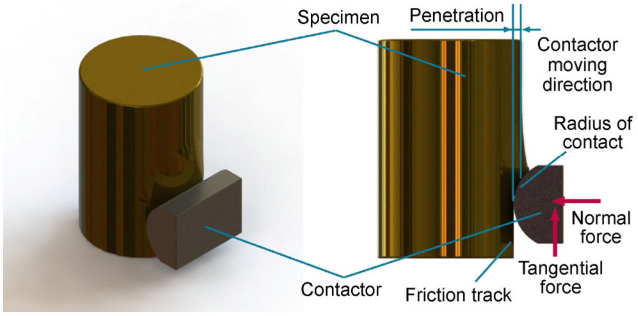

**Fig. 24** Warm Hot Upsetting Sliding Sliding Test (WHUST). Reproduced with permission from Ref. [59]. Copyright Springer, 2015.

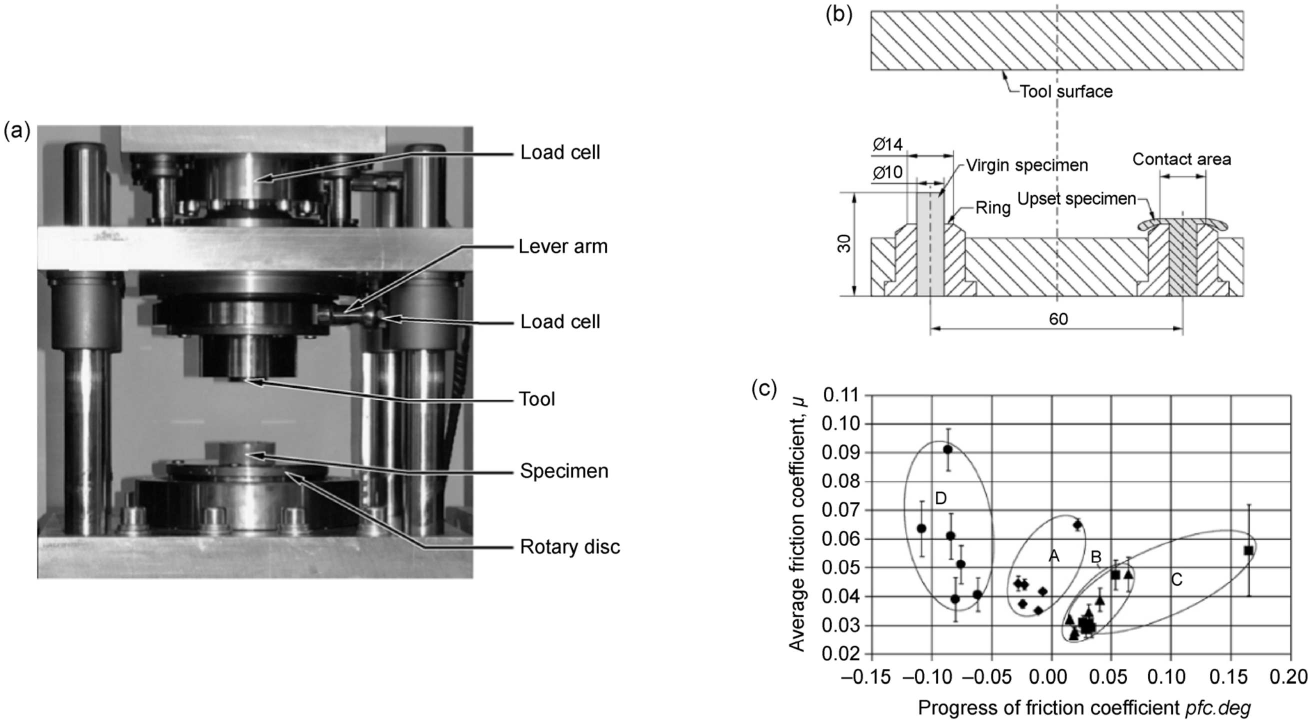

**Fig. 25** (a) The rotational forging tribometer testing device; (b) schematic of the experiment; (c) average friction coefficients of lubricants (A, B, C, and D represent different lubricants). Reproduced with permission from Ref. [60]. Copyright Elsevier, 2014.

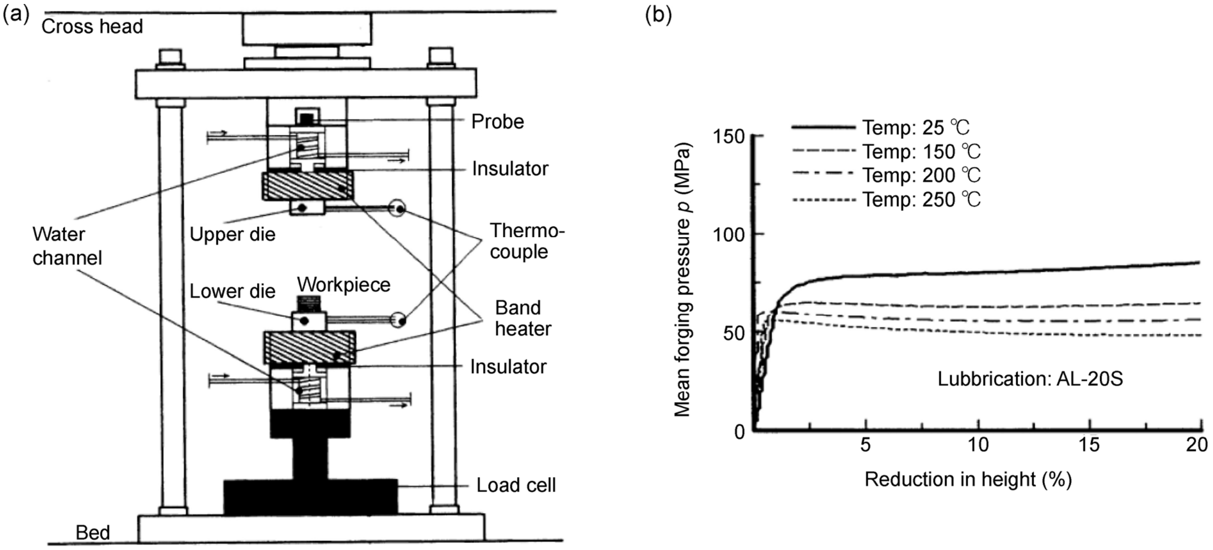

**Fig. 26** (a) Schematic of the ultrasonic reflection intensity evaluation test; (b) relationship between reduction in height and mean forging pressure (lubricated condition). Reproduced with permission from Ref. [89]. Copyright Elsevier, 2014.

### 5.3 Tribometer for rolling

Iida et al. designed a simulative seamless pipe hot rolling test to investigate the influence of compositions and thickness of the iron oxide layer on lubricity [90]. In the testing apparatus, the workpiece was rolled between the roller and the flat die (tool) as shown in Fig. 27(a). Lubricant was also applied on the interface between the workpiece and the flat die. The friction coefficient was calculated with the rolling load and the friction between the flat die and the workpiece. The obtained values of friction coefficient and scoring with different rolling loads are shown in Fig. 27(b).

**Table 4** Coefficients of friction under various conditions obtained from different tribometers for bulk metal forming at high temperatures.

| Types | Authors | Material pairs | Lubricants | Temperatures | COF |
|---|---|---|---|---|---|
| Ball-on-disc test | Wang et al. (2010) | H-11 tool steel/AA7475 | Dry | 25 °C | 0.40–0.70 |
| | | H-11 tool steel/AA7475 | Dry | 300 °C | 0.60–1.10 |
| | | H-11 tool steel/AA7475 | Dry | 400 °C | 0.65–1.30 |
| | | H-11 tool steel/AA7475 | Dry | 450 °C | 1.10–1.60 |
| Block-on-disc test | Pellizzari (2011) | PVD TiAlN steel/AA6082 | Dry | 250–350 °C | 0.75–1.00 |
| | | PVD CrN steel/AA6082 | Dry | 250–350 °C | 0.50–1.00 |
| | | CVD TiC+TiN steel/AA6082 | Dry | 250–350 °C | 0.70–0.80 |
| Block-on-cylinder test | Björk et al. (1999) | H13 tool steel/AA6063 | Dry | Room–620 °C | 1.00–1.50 |
| Ring compression test | Li et al. (2001) | Tool steel/Ti-6Al-4V | Graphite power | 750–1000 °C | 0.22–0.95$^{*}$ |
| | Matsumoto & Osada (2002) | WC tool/ZK60 Magnesium | Several lubricants | 200 °C | 0.10–0.33 |
| Sliding test | Peterson et al. (1994) | Various materials/Various materials | $Cu(ReO_4)_2$ | Room–700 °C | 0.15–0.50 |
| | Matsumoto & Osada (2002) | Different coated tools/ZK60 Magnesium | Dry | Room–100 °C | 0.06–0.12 |
| | Mosaddegh et al. (2011) | Steel/Steel | Dry | 577 °C | 0.40–0.60 |
| | | Steel/NBK7 glass | Dry | 577 °C | 0.20–0.55 |
| Upsetting sliding test | Daouben et al. (2008) | Nitrided tool steel/Medium alloy steel | Graphite suspension | 1100 °C | N/A |
| Rotational forging test | Buchner et al. (2008) | 1.2344 tool steel/AA2618 | Various lubricants | 250–450 °C | 0.03–0.09 |
| Non-contact test | Saiki et al. (2006) | JIS-SKD61/JIS-A1050 | 50%-diluted Hot-aqua-lub | 250–450 °C | N/A |

Note: * is friction factor *m*

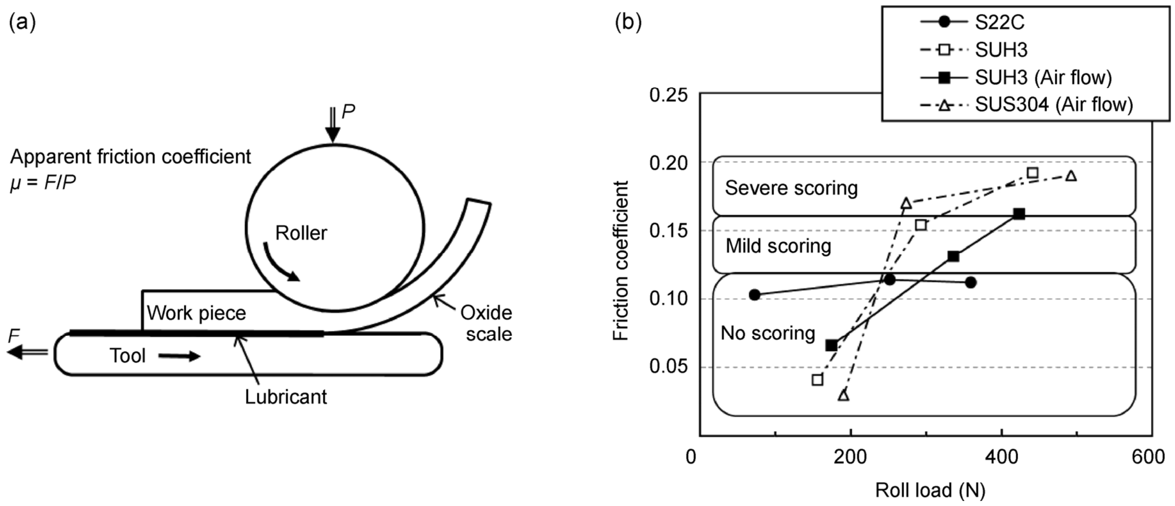

**Fig. 27** Tribometer for rolling developed by Iida and Hidaka: (a) schematic of the tribometer and (b) effects of rolling load on friction coefficient and scoring. Reproduced with permission from Ref. [90].

### 5.4 Discussions on high temperature tribometers

Based on the selected tribometers, most of them could be used to capture friction coefficients at high temperatures. However, only a few of them provide direct friction coefficient measurements. In metal forming, a workpiece is under plastic deformation and its surface expansion ratio can be very high, particularly for bulk forming. As a result, direct measurement of friction coefficient is extremely crucial for a tribometer in order to obtain accurate friction values. It can be observed that many of the tribometer tests at high temperatures were carried out under dry lubrication. This poses a serious tribological concern because lubricant is extremely useful to avoid the tool-workpiece contact. As a result, advanced research in new lubricants and new surface treatments for metal forming at high temperatures must be carried out. Certainly, tribometers that can accurately and reliably evaluate tribological characteristics at high temperatures are necessary.

Testing results from newly developed tribometers can provide more information about the tribological characteristics of metal forming at elevated temperatures. These information is extremely crucial for the understanding of interactions between tool and workpiece. In addition, a better understanding about the occurrence and prevention of galling conditions/mechanism can also be investigated by using tribometers for metal forming at high temperatures.

## 6 Conclusions

Several criteria and observations on oxide layers in hot rolling and hot stamping were reviewed and summarized. Friction and wear mechanisms of oxide layers in different processes and conditions were explained, particularly on high strength steels. It was found that the development of layers at the interface of two materials contributed to the reduction of friction and wear rate.

Surface coatings on both tool and workpiece helped improve friction and wear at elevated temperatures. However, heat treatment, surface roughness, and coating layers had influences on the performance of tool surface coatings. Al–Si and Zn–Ni coatings were commonly applied to high strength steel sheets for applications at elevated temperatures.

Lubricants were not widely used in many hot forming applications. However, some common solid lubricants such as graphite were typically used in hot forging and extrusion. More research works to explore new lubricants for hot forming applications should be carried out.

Tribometers for metal forming at high temperatures were presented and categorized by three forming processes: sheet forming, bulk forming and rolling. Many of the tribometers were able to capture the friction values of tool-workpiece interfaces by controlling critical parameters, such as contact pressure, relative sliding velocity, and surface temperature. However, some of them were not able to represent the actual forming conditions by taking into account of workpiece surface expansion during forming. In addition, some of them could not directly measure friction values and their obtained friction value accuracy was heavily relied on the modeling accuracy of material behaviors and testing conditions. Consequently, tribometers should be improved to measure tribological characteristics at many untested conditions at elevated temperatures.

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