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Friction in metal forming processes: a comprehensive review of experimental methods, influencing factors, and surface engineering approaches

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Abstract

Friction is a critical factor in metal forming processes, influencing material flow, surface quality, tool life, and overall production efficiency. This comprehensive review explores the experimental methods employed to evaluate friction behavior in metal forming, including pin-on-disk tests, ring compression tests, stretch forming tests, and tribometers. The integration of advanced measurement technologies such as infrared thermography, digital image correlation, and high-speed imaging has significantly improved the accuracy of friction assessments. Furthermore, the review highlights the key parameters affecting friction, including lubrication conditions, material pairings, surface roughness, and process temperature. Surface engineering strategies, such as coatings and texturing, are also discussed as effective approaches to control friction. The insights provided aim to support researchers and practitioners in selecting suitable evaluation techniques and in developing optimized surface treatments for enhanced metal forming performance.

Keywords Friction, Metal forming, Tribology, Pin-on-disk test, Tribometer, Lubrication

Introduction

Friction is a critical factor in metal forming operations, influencing the material flow, tool wear, surface finish, and overall process efficiency. Experimental evaluation of friction in metal forming is essential for optimizing processes, improving tool life, and ensuring high-quality products. Recent advancements in experimental techniques have provided new insights into the mechanisms

of friction, as well as methods for its measurement and control.

This section presents an overview of experimental methods for evaluating friction in metal forming, with a focus on recent studies and innovations (Camacho et al. (n.d.)); Sigvant et al. 2019; Wu et al. 2025).

Methods of experimental evaluation of friction

Various experimental techniques are employed to evaluate friction in metal-forming processes. The key methods are given below.

Pin-on-Disk Test is one of the most commonly used methods for evaluating friction in metal forming. It involves placing a pin (representing the tool or

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workpiece) in contact with a rotating disk (representing the counter surface) under controlled loads and speeds. Studies have integrated advanced sensors, such as infrared thermography and laser-induced fluorescence, to measure the frictional heat and surface wear in real time (Puccio et al. 2024; Salguero et al., 2025; Velkavrh et al. 2025) (Fig 1).

In this test configuration, a stationary pin is mounted vertically and pressed against a rotating disc under a constant applied load via a dead weight. The arm holds the pin in place and is connected to a force transducer or measuring instrument to detect the frictional force developed during sliding. As the disc rotates, a circular wear track is formed on the disc surface. This method is widely used to evaluate the tribological performance of materials under dry or lubricated sliding conditions, following standards such as ASTM G99.

Ring Compression Test is frequently used in forging and extrusion processes to evaluate frictional conditions at high pressures. The test involves compressing a ring-shaped specimen between two dies, and the frictional force is measured during compression. Advances in high-temperature testing have enabled friction evaluation under hot-working conditions, providing more accurate simulations of industrial processes (Real-Time Quality Monitoring of Laser Cladding Process on Rail Steel by an Infrared Camera (n.d.)); Effects of Coating and Lubrication on Friction and Wear for Metal-to-Metal Application | Request PDF. 2024; Investigation on blasted tool surfaces as a measure for material flow control in sheet-bulk metal forming. 2024). In sheet metal forming, the stretch forming test is commonly used to evaluate friction and lubrication. This test involves stretching a metal sheet over a die while measuring the frictional forces and deformations. High-speed cameras and digital image

correlation (DIC) techniques have been used in recent studies to monitor surface deformation and frictional behavior in real-time (Investigation on blasted tool surfaces as a measure for material flow control in sheet-bulk metal forming. 2024; An alternative evaluation method for friction condition in cold forging by ring with boss compression test. 2024) (Fig. 2).

The ring compression test is employed to evaluate the friction conditions between specimens and die surfaces during deformation. The specimen, with outer and inner diameters of 15 mm and 9 mm respectively, and a height of 2 mm, is placed between two flat dies. Upon compression, the change in internal diameter from d_0 to d_1 is measured. A decrease in the internal diameter indicates higher friction, while an increase reflects lower interfacial friction. After deformation, the specimen height reduces to 1 mm. This method follows standard guidelines for assessing friction in bulk metal forming processes.

Tribometers are devices specifically designed to measure friction under controlled conditions. These devices can measure both static and dynamic friction at varying speeds, pressures, and temperatures. They are commonly used in laboratory settings to simulate specific conditions in metal forming. The latest tribometers are capable of simulating a wide range of conditions, such as multi-axial loading and elevated temperatures, and are equipped with real-time data logging systems for precise analysis (An alternative evaluation method for friction condition in cold forging by ring with boss compression test. 2024; Petre et al. 2025; Ramalho and Vilhena 2025) (Fig. 3).

The MFT 1.0 is designed to evaluate tribological behavior under simulated metal forming conditions. In this setup, a specimen is positioned between two anvils and subjected to combined normal and tangential loads. The system measures axial force, frictional force, and material

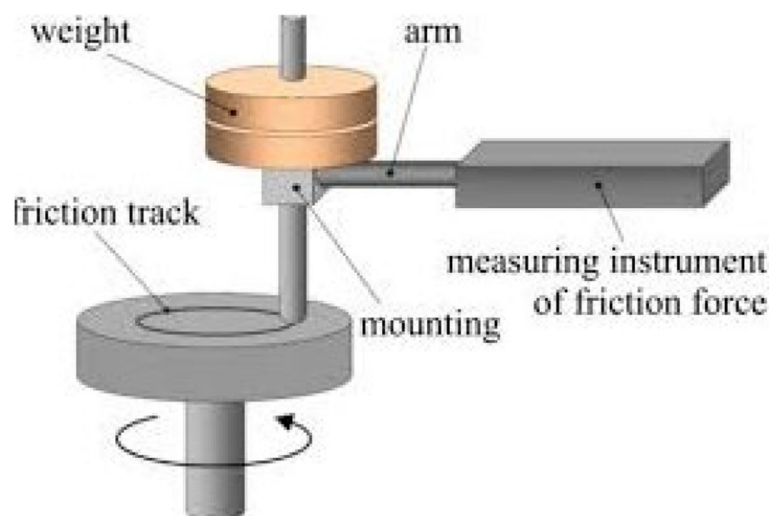


Fig. 1 Schematic illustration of pin-on-disc test (Trzepieciniski and Lemu 2020)

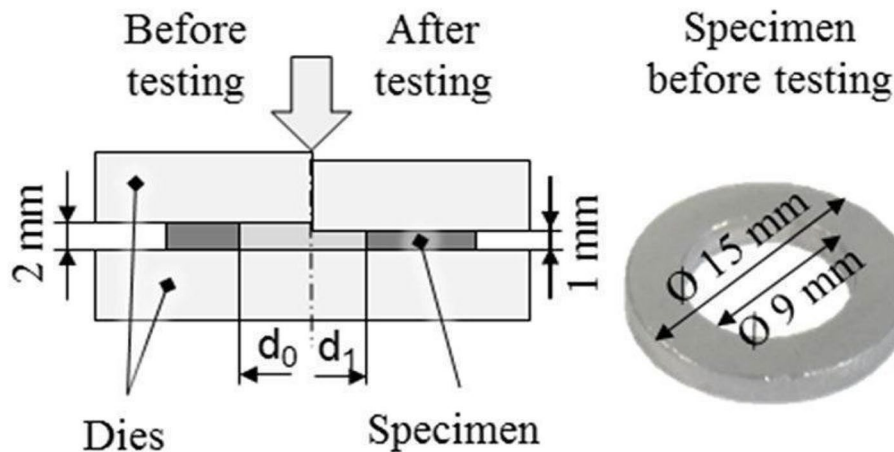


Fig. 2 Schematic diagram of the ring compression test setup and specimen geometry (Investigation on blasted tool surfaces as a measure for material flow control in sheet-bulk metal forming. 2024)

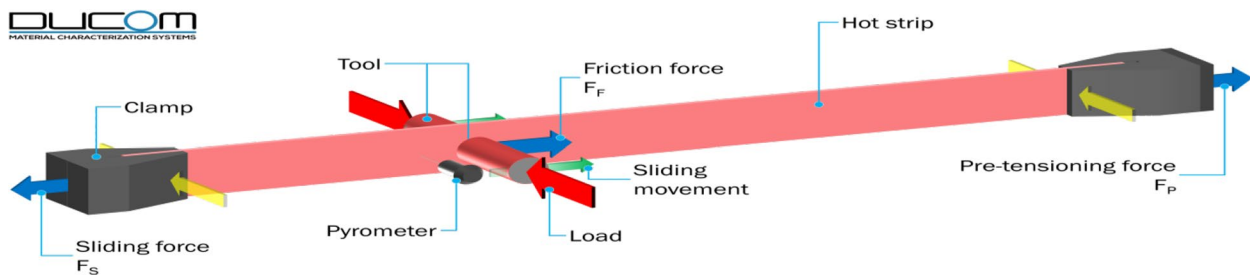


Fig. 3 Schematic representation of force measurements in the Metal Forming Tribometer (MFT 1.0) (G. A. Team (n.d.))

flow using integrated force sensors. Normal force is applied perpendicularly through the top anvil, while tangential forces are induced by relative sliding between contact surfaces. This configuration enables the precise determination of friction coefficients and material resistance under conditions closely resembling industrial forming operations.

Finite Element Method (FEM) Simulation: it has been widely adopted to predict the frictional behavior during metal forming. Although not strictly experimental, FEM models allow for the integration of experimental data to simulate various friction conditions and predict the outcomes of different process parameters. Coupling experimental data with FEM models has led to more accurate predictions of frictional forces, heat generation, and tool wear in complex metal-forming processes (Study of Tool Wear in Friction Stir Processing of Metal Matrix Composites—A Review (n.d.)); Mia et al. 2025; Anggono et al (n.d.). Recent research has focused on enhancing the accuracy of experimental methods for evaluating friction and providing deeper insights into the influence of friction on metal forming. Below are some key findings from recent studies.

Impact of Temperature and Velocity on Friction: In a recent study, the effects of temperature and sliding velocity on friction during hot and cold forging processes were

investigated. The results indicated that friction coefficients decreased as velocity increased. However, at higher temperatures, the material softened, leading to a higher friction coefficient. This highlighted the importance of accurate temperature control in high-temperature metal forming operations to effectively manage friction and improve material flow (Domitner et al. 2021; Mozgovoy et al (n.d.); Wang et al. 2025).

Role of Lubrication in Friction Reduction: Lubrication plays a vital role in reducing friction and wear in metal forming. The research conducted experiments to compare the frictional behavior of different lubricants in sheet metal forming processes. Their results showed that solid lubricants, such as graphite, significantly reduced friction compared to conventional oils and greases. These findings have important implications for industries seeking to improve surface quality and extend tool life in high-speed forming operations (Aiman et al. 2024; Folle et al. 2025).

Friction in High-Speed Forming: The study explored friction at high velocities using a high-speed pin-on-disk tribometer. They found that frictional forces increased with velocity, particularly in the case of dry contact. Their results suggested that reducing friction in high-speed forming processes requires the development of advanced lubrication systems capable of maintaining a

thin lubricant film even at elevated speeds (Pereira et al. 2024; Huang and Wu (n.d.)).

Friction-Induced Heat Generation: The study investigated friction-induced heat generation during extrusion processes. The researchers used infrared thermography to measure temperature variations in real time and found that friction-induced heating could lead to undesirable temperature gradients, which affected the material, flow and caused surface defects. This study highlighted the need for better temperature control systems in extrusion and other high-speed metal forming operations (Infrared thermography for monitoring heat generation in a linear friction welding process of Ti6Al4V alloy | Request PDF. 2024; Rangel et al. (n.d.)); Kisuka et al. 2025).

Wear Mechanisms and Tool Life: A study examined the wear mechanisms that occur as a result of friction in metal forming. The findings revealed that tool wear is strongly influenced by the friction coefficient, with higher friction leading to increased wear and shorter tool life. Additionally, it was found that frictional heat contributed to the softening of tool materials, accelerating wear during high-temperature operations (Wear mechanism and tool life prediction of high-strength vermicular graphite cast iron tools for high-efficiency cutting - ScienceDirect (n.d.)); Gupta et al. 2023; Zong et al. 2024) (Fig 4).

Influence of temperature and sliding velocity

Friction, a critical phenomenon in tribology, is highly sensitive to changes in both temperature and sliding velocity. The interplay between these two parameters can drastically alter the frictional behavior of materials, influencing wear rates, energy efficiency, and the lifespan of mechanical components. At elevated temperatures, materials may undergo softening, oxidation, or phase transformations, all of which can modify surface interactions. Simultaneously, increased sliding velocity can raise interface temperatures due to frictional heating, further compounding thermal effects and potentially leading to

lubrication breakdown, adhesive wear, or the formation of tribo films (Myshkin et al. 2005; Essam et al. (n.d.); Kurdi et al. 2020).

Recent experimental and computational studies have contributed significantly to our understanding of how temperature and sliding speed interact in real-world applications, ranging from automotive braking systems and aerospace components to biomedical implants and manufacturing tools. These investigations reveal that the relationship is far from linear friction coefficients may increase, decrease, or stabilize depending on the material pair, contact pressure, environment, and surface roughness. For instance, metals often exhibit a transition from boundary to mixed or hydrodynamic lubrication regimes with increasing velocity, while polymers may experience thermal softening that lowers friction after a certain threshold.

Understanding these complex interactions is essential for designing more durable and efficient mechanical systems. By fine-tuning operational parameters such as speed and temperature, or by selecting appropriate materials and lubricants, engineers can mitigate adverse frictional effects. Therefore, ongoing research continues to explore these dynamics to better predict and control frictional behavior under varying service conditions (Ice friction: the effect of thermal conductivity | Journal of Glaciology | Cambridge Core (n.d.)); Essam et al. 2025). Temperature variations can alter the physical properties of materials, leading to changes in friction coefficients. For instance, research on polytetrafluoroethylene (PTFE) indicates that its coefficient of friction increases notably around 20 °C, corresponding with a phase transition in the material. Similarly, studies on ice have shown that at temperatures above -10 °C and sliding velocities greater than approximately 0.01 m/s, frictional heating is sufficient to melt the ice surface, forming a lubricating water film that reduces friction (Ice friction: the effect of

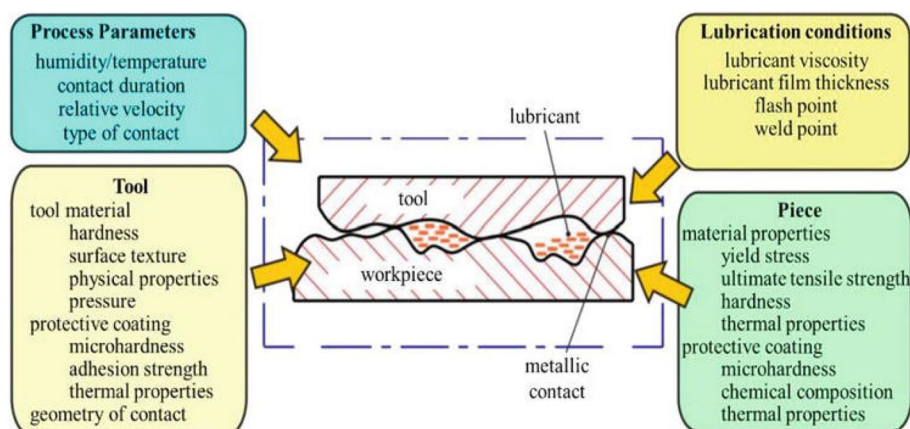


Fig. 4 Parameters that can influence the friction in metal forming (Trzepieciniski and Lemu 2020)

thermal conductivity | *Journal of Glaciology* | Cambridge Core (n.d.); Flom and Porile 1955).

The speed at which two surfaces slide against each other also plays a crucial role in frictional behavior. In the context of ice, higher sliding velocities can lead to increased frictional heating, promoting surface melting and thus lowering friction due to the lubricating effect of the melt water. Conversely, at lower velocities, insufficient heat is generated to melt the ice, resulting in higher friction due to direct solid–solid contact (Ice friction: the effect of thermal conductivity | *Journal of Glaciology* | Cambridge Core (n.d.)).

The combined effects of temperature and sliding velocity can lead to complex frictional behaviors. For example, a study on aluminum particles sliding over graphene layers demonstrated that increasing temperature leads to a decrease in the kinetic friction coefficient, suggesting that thermal activation facilitates easier sliding at the nanoscale. Additionally, research on tire-pavement interactions under hot weather conditions revealed that higher ambient temperatures and increased sliding speeds contribute to reduced skid resistance, emphasizing the importance of considering both factors in pavement design (Tang et al. 2018; Kheiri and Tsukanov 2023).

Friction heat generation

Friction-induced heat generation plays a pivotal role in numerous mechanical systems, influencing performance, wear, and longevity. Recent research has delved into the mechanisms of heat generation due to friction, employing both experimental and computational approaches to elucidate this complex phenomenon.

At the microscopic level, frictional heat arises from the relative motion between contacting surfaces, leading to energy dissipation as heat. A study published in *Physics of Fluids* analyzed heat generation in magnetorheological fluids under shear, attributing internal friction to microstructural interactions within the fluid (X (李学利) et al. 2025; Mishra et al. 2024). Similarly, related research evaluated theoretical models that predict temperature increases resulting from friction between particles, highlighting the crucial role of contact mechanics in heat generation (Kisuka et al. 2021, 2024).

Operating parameters such as sliding velocity, normal load, and environmental temperature significantly impact frictional heat generation. For instance, a study demonstrated that frictional heat significantly influences the nonlinear modal characteristics of mechanical systems, leading to complex behaviors such as softening and stiffening under varying conditions (Gao et al. 2024; Yuan et al. 2024). Molecular dynamics simulations have also provided insights into how high sliding velocities contribute

to transient thermal responses at the nanoscale (Kheiri and Tsukanov 2023; Yeo and Jang 2010).

The accumulation of frictional heat can lead to material degradation and increased wear rates. Research has explored how frictional heat influences wear, taking into account factors such as initial contact pressure and relative slip velocity (Sun and Zheng 2024; Sun et al. (n.d.)). Understanding these relationships is crucial for predicting component lifespan and performance. Recent studies have provided graphical data illustrating the relationship between frictional heat generation and operational parameters (Fig. 5).

Friction Heat Generation Rate vs. Rotational Speed: A graph from a study on spindle-bearing systems shows that as rotational speed increases, the rate of frictional heat generation also rises, emphasizing the need for thermal management in high-speed applications (Thermal Characteristic Analysis and Experimental Study of a Spindle-Bearing System (n.d.); Wu and Tan (n.d.)).

Friction between metallic layers

Recent research has provided significant insights into the frictional behavior between metallic layers, focusing on how interfacial interactions and structural modifications influence friction coefficients.

A notable study investigated the frictional properties of gold-nickel (Au-Ni) multilayers with varying individual layer thicknesses (10 nm, 20 nm, 50 nm, and 100 nm) under ultrahigh vacuum conditions. The findings revealed that thinner layers (10 nm and 20 nm) experienced significant intermixing due to shear forces during sliding, leading to the formation of a metastable Au-Ni alloy with ultrafine grains. This grain refinement increased grain boundary-mediated deformation, resulting in lower friction coefficients. Conversely, thicker layers (50 nm and 100 nm) exhibited less intermixing and higher friction coefficients, attributed to a transition from grain boundary-mediated to dislocation-mediated deformation mechanisms (Cihan et al., 2019; Chandross et al. (n.d.)).

Another study focused on Vander Waals heterostructures composed of two-dimensional (2D) materials, such as graphene/MoS₂, graphene/PdSe₂, and MoS₂/PdSe₂. The research demonstrated that heterostructures with greater differences in ionicity between the constituent 2D materials exhibited lower interlayer friction coefficients (approximately 0.001). This reduction in friction is attributed to weaker interfacial interactions and diminished charge transfer. In contrast, heterostructures with smaller ionicity differences, like MoS₂/PdSe₂, showed higher friction coefficients (around 0.02) due to stronger interfacial adhesion and increased charge transfer. These findings suggest that selecting 2D material pairs with significant ionicity differences can be an effective strategy

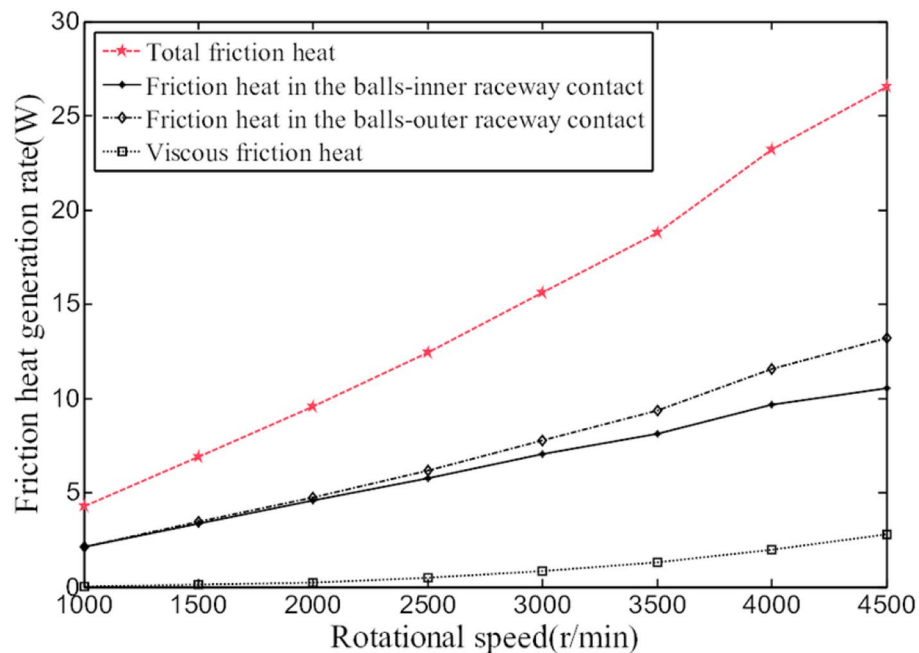


Fig. 5 Friction heat generation rate vs. rotational speed ($P_a = 350$ N) (Thermal Characteristic Analysis and Experimental Study of a Spindle-Bearing System (n.d.))

for achieving ultralow friction in nanoscale applications (Ru et al. 2024) (Fig 6).

The study on Au-Ni multilayers includes high-angle annular dark field (HAADF) scanning transmission electron microscopy (STEM) images illustrating the cross-sectional microstructures of the as-grown and worn multilayers. These images depict the extent of intermixing and structural changes post-sliding, highlighting the correlation between layer thickness, microstructural evolution, and frictional behavior.

These studies underscore the critical role of interfacial interactions, material selection, and structural modifications in governing friction between metallic layers. Understanding these factors is essential for designing advanced materials and interfaces with tailored frictional properties for applications in microelectromechanical systems (MEMS), nanoelectronics, and other technologies requiring precise control over friction and wear (Cihan et al. 2019; Klenov and Stemmer 2006).

Friction lubrication carrier layer

Recent advancements in lubrication technology have focused on the development of carrier layers that enhance friction reduction and wear resistance. These carrier layers often incorporate nanomaterials or biopolymers to improve the performance of lubricants.

Graphene nanoplatelets (GNPs) have been extensively studied as additives in lubricants due to their excellent mechanical and thermal properties (Sikdar et al. 2023). A study published in ACS Omega investigated the

tribological performance of a multilayer graphene-reinforced TiO_2 composite as a nanolubricant additive. The results demonstrated that incorporating 1.0 wt% of this composite into base oil significantly reduced the friction coefficient and wear scar diameter, indicating enhanced lubrication performance (Preparation and Tribological Properties of a Multilayer Graphene-Reinforced TiO_2 Composite Nanolubricant Additive | ACS Omega (n.d.)). Similarly, related research investigated the effects of graphene nanoplatelets combined with bacterial cellulose in polyol ester (POE) oil. The study found that this combination led to a substantial decrease in the coefficient of friction, suggesting a synergistic effect between graphene and bacterial cellulose in forming an effective lubrication carrier layer (Fuadi 2022). Cellulose derivatives have also been identified as promising candidates for lubrication carrier layers. An article discussed the use of bio coatings and additives, such as methylated and ethylated cellulose pulps, which, when dispersed in vegetable oils, formed gel-like structures that significantly reduced friction coefficients compared to commercial lubricating greases (Full article: Biocoatings and additives as promising candidates for ultralow friction systems (n.d.)). The incorporation of nanoparticles like molybdenum disulfide (MoS_2) has been shown to improve lubrication properties. A study in Langmuir examined oleic acid-modified MoS_2 in lithium-based grease under boundary lubrication conditions. The modified MoS_2 formed a stable lubricant film on metal surfaces, reducing friction and wear more effectively than unmodified MoS_2 (Guo et al. 2023).

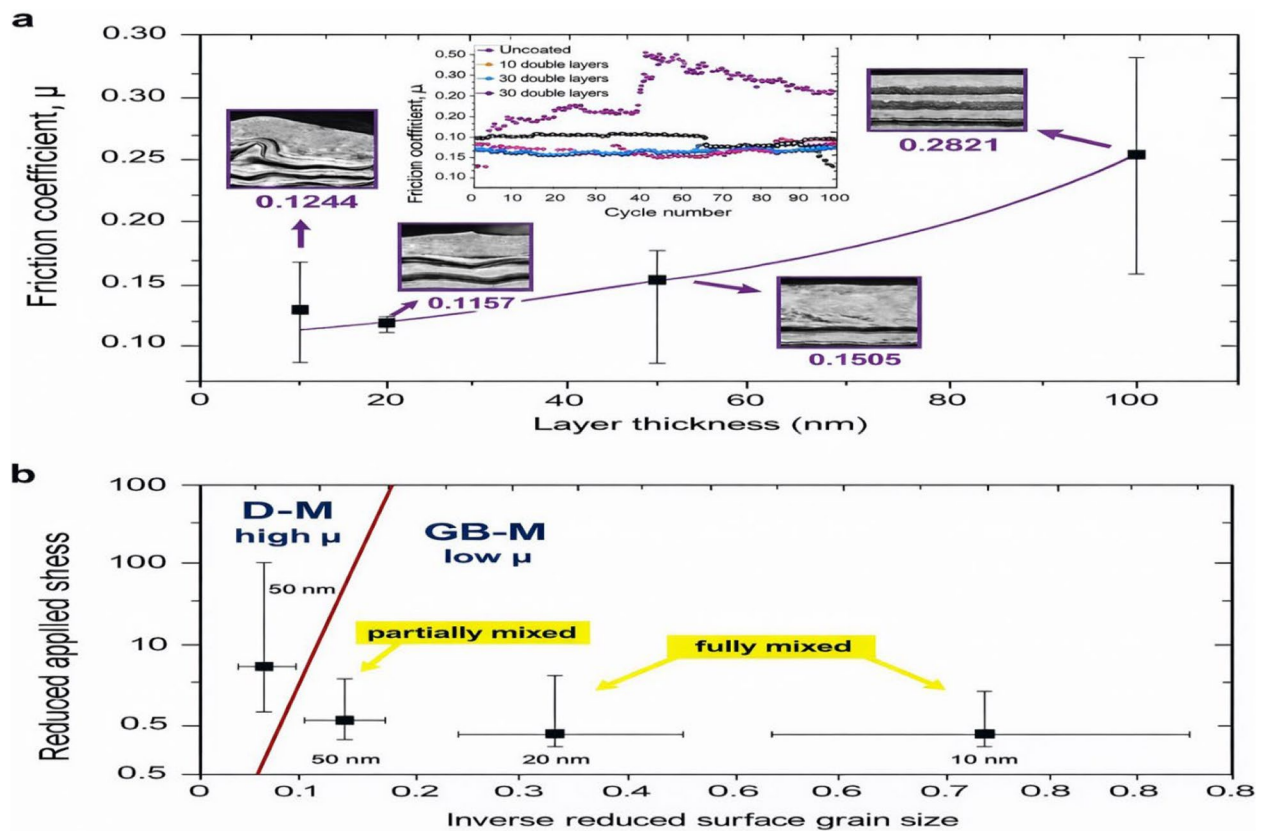


Fig. 6 Frictional behavior of Au-Ni multilayers and the relationship between microstructure, deformation mechanism, and friction (Cihan et al. 2019)

The image illustrates the friction and wear mechanisms for solid lubrication at low temperatures, highlighting the effects of physical and mechanical interactions, transfer film formation, and thermally activated processes.

Figure (7a): physical and mechanical effects.

Figure (7a) illustrates how variations in temperature influence friction through changes in contact mechanics. At room temperature, the contacting surfaces are characterized by rough profiles with contact occurring primarily at surface asperities tiny high points that bear the load. Under these conditions, the coefficient of friction (μ) is determined by the shear stress (τ), the real contact area (A_r), and the applied normal load (N). The materials at room temperature exhibit moderate surface deformation, allowing for more conformal contact and relatively stable friction behavior.

In contrast, at cryogenic or low temperatures, the materials become significantly more brittle, and their elastic modulus increases. This change leads to a reduction in surface compliance, resulting in less deformation under load. Consequently, the real contact area decreases, and the materials are more prone to brittle delamination a form of mechanical failure where surface layers fracture and separate. These effects contribute to increased friction and wear, as the stiffer material cannot adapt easily

to surface irregularities, leading to localized stress concentrations and material damage during sliding.

Figure (7b) highlights the role of chemical and molecular-level processes in the development of transfer films and their effect on frictional behavior. At room temperature, the polymer chains such as those in PTFE (polytetrafluoroethylene) possess sufficient molecular mobility to undergo reorientation. This molecular movement enables the formation of a low-friction interface through the generation of a transfer film on the counter surface. These films are created via tribo chemical reactions, which are initiated by the frictional energy at the sliding interface. In the case of PTFE, the fluorocarbon chains align and interact with the counter surface to form a stable, lubricating film that significantly reduces friction.

However, at lower temperatures, the situation changes drastically. The decrease in thermal energy leads to inhibited molecular mobility and reduced chemical activity. Under these conditions, the polymer chains are unable to reorient effectively, and the tribo chemical reactions necessary for transfer film formation are suppressed. As a result, transfer films either do not form or are significantly less effective, leading to increased friction and a decline in lubrication performance. This emphasizes the critical role of temperature in enabling or hindering tribological mechanisms at the molecular scale.

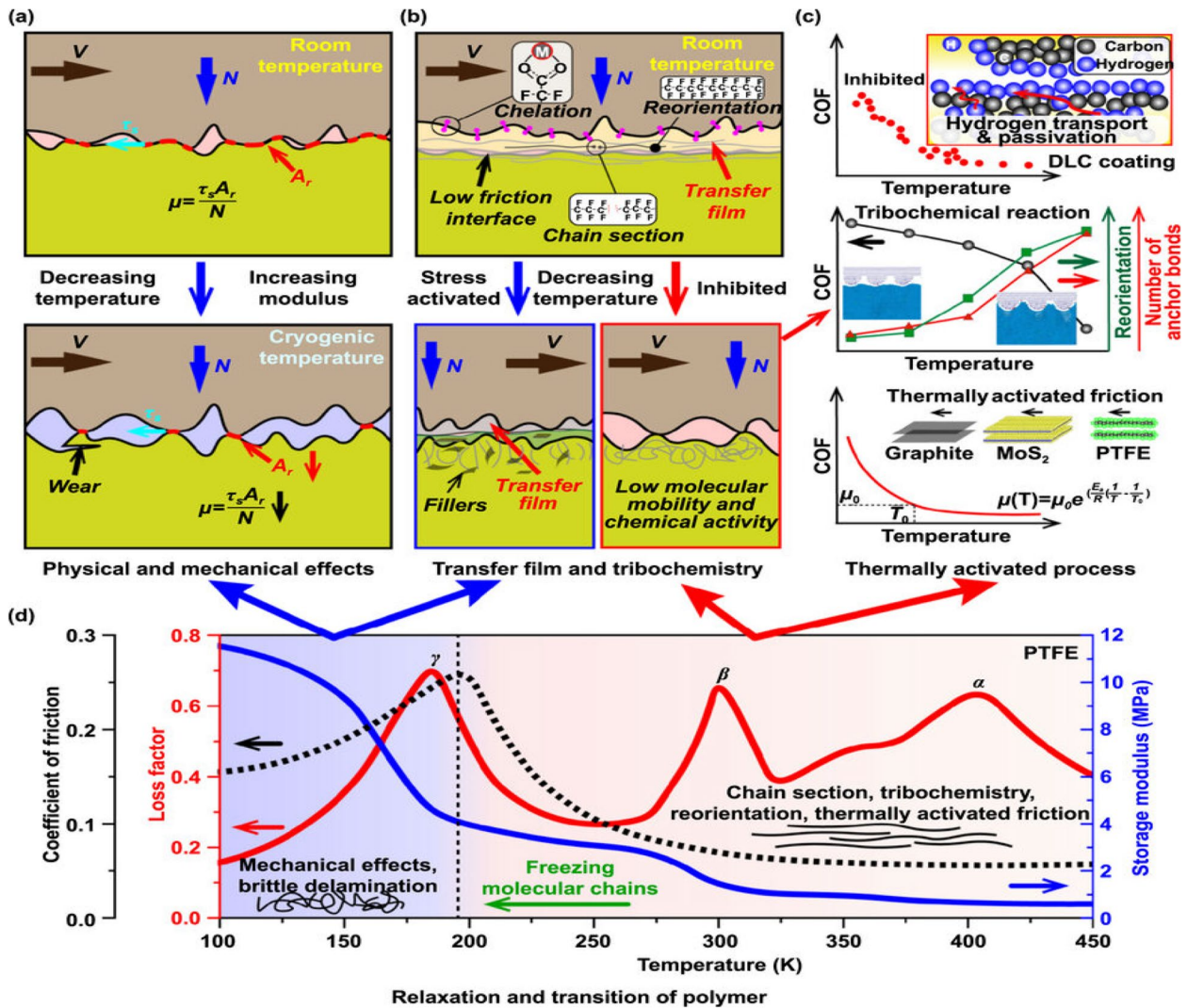


Fig. 7 (a,b,c,d). illustrates the mechanisms of friction and wear for solid lubrication at low temperatures (Progresses on cryo-tribology 2025)

Figure (7c) explores how temperature affects chemical and physical mechanisms related to friction, particularly in materials with thermally sensitive tribological properties.

At the top, the diagram focuses on diamond-like carbon (DLC) coatings. At low temperatures, the transport of hydrogen atoms within the material is significantly inhibited, which disrupts surface passivation a key process where reactive surface sites are neutralized to reduce friction. As a result, the frictional performance of DLC coatings deteriorates in cryogenic environments due to reduced hydrogen mobility.

In the middle section, the figure highlights tribo chemical systems, where chemical reactions at the sliding interface are activated by frictional energy. These tribo chemical reactions increase with temperature, enhancing lubrication performance and decreasing the coefficient of friction (COF). However, in cold environments, these

reactions are suppressed due to limited molecular mobility and energy availability. This suppression leads to a decline in the formation of protective tribo films, resulting in increased friction and wear.

The bottom part presents a thermally activated model of friction for materials such as graphite, molybdenum disulfide (MoS₂), and PTFE. These materials exhibit a decrease in friction as temperature rises, described by the exponential decay function:

$$\mu(T) = \mu_0 \exp\left(\frac{E_a}{R} \left(\frac{1}{T} - \frac{1}{T_c}\right)\right) \quad (1)$$

Here, $\mu(T)$ is the temperature-dependent coefficient of friction, μ_0 is the reference friction value, E_a is the activation energy, R is the gas constant, T is the working temperature, and T_c is a characteristic temperature. This relationship indicates that as the temperature increases,

the energy barriers for sliding are more easily overcome, leading to a reduction in friction due to more efficient sliding mechanisms at the atomic level.

Figure (7d) presents a comprehensive graph that correlates temperature with key tribological and mechanical properties of polymers, including the coefficient of friction (COF), loss factor, and storage modulus (a measure of material stiffness). The x-axis represents temperature in Kelvin (K), while the left y-axis shows the COF and loss factor and the right y-axis represents the storage modulus.

In the blue region (approximately 100–150 K), polymers exhibit high stiffness (evident from the high storage modulus) and low energy dissipation (low loss factor), indicating that the material is brittle and rigid. In this range, the COF is relatively high due to mechanical effects like brittle delamination, where the surface layers crack and fail under stress due to limited deformation capability.

Moving into the middle-temperature range (around 200 K), there is a noticeable transition in the behavior of the polymer chains. At this stage, molecular chains begin to freeze, reducing their motion and reactivity. The graph shows distinct peaks in the loss factor, labeled as γ , β , and α , which correspond to glass transition processes and segmental relaxations within the polymer. These transitions represent changes in the molecular mobility that affect the material's ability to dissipate energy and adjust to frictional forces. In the red region (extending toward room temperature and above), the polymer gains greater molecular mobility, allowing for the formation of transfer films and the activation of tribochemical reactions. As a result, the coefficient of friction decreases, making this the optimal temperature range for low-friction performance. The presence of multiple loss factor peaks in this region indicates ongoing molecular relaxation transitions, which further support the material's ability to adapt to stress and maintain effective lubrication.

Overall, this figure underscores the critical influence of temperature on the mechanical and tribological performance of polymer-based lubricants, showing how transitions in molecular behavior directly affect friction and wear characteristics.

In general, at low temperatures, polymers tend to become brittle, which impedes their ability to undergo physical deformation and limits the effectiveness of chemical lubrication. In such conditions, the performance of the material is significantly hindered. Transfer films, which are essential for low-friction performance, rely on temperature-driven molecular mobility to form properly. At higher temperatures, thermally activated friction mechanisms come into play, resulting in a reduction in friction as the material becomes more flexible and less resistant to deformation. For reliable performance

across a range of temperatures, it is crucial to design lubricants and materials that account for these thermal transitions, ensuring that both the frictional properties and the structural integrity of the material remain consistent under varying thermal conditions.

Table 1 provides a critical comparative analysis of the principal experimental, numerical, and data-driven methods used to evaluate friction in metal forming. The comparison highlights differences in accuracy, limitations, and applicable forming conditions, thereby supporting informed method selection and identifying research gaps.

Surface treatment of forming processes

Surface treatment of forming processes plays a vital role in enhancing the performance, durability, and efficiency of materials involved in manufacturing. These treatments are designed to improve the surface properties of metals, polymers, and other materials to withstand wear, corrosion, and high-stress conditions during forming operations (Ramezani et al. 2023; Salman et al. 2025) (Fig. 8).

Below is a comprehensive overview of key surface treatment techniques used in forming processes:

a) Laser cladding for die enhancement

Laser cladding has emerged as an effective method to enhance the surface properties of hot press forming dies. This technique involves melting a powder material onto the substrate using a laser beam, resulting in a metallurgical bond with minimal dilution. Factors influencing the quality of cladding include process parameters, bonding strength, and powder characteristics. Optimizing these parameters leads to improved surface integrity and performance of the dies (Norhafzan et al. 2021; Zhao et al. 2023; Norhafzan et al. (n.d.); Zhong and Liu (n.d.)) (Fig. 9).

b) Plasma surface treatment techniques

Plasma activation is a surface modification method that employs plasma processing to enhance the adhesion properties of various materials, including metals, polymers, and textiles. This process introduces functional groups onto the material's surface, improving bonding, coating, and painting characteristics. Plasma activation can be performed at atmospheric pressure using gases like air, hydrogen, nitrogen, or oxygen, offering advantages in cost, safety, and environmental impact (Plasma activation. 2023; Haji and Kan (n.d.); Kim et al. 2025; Hegemann et al. (n.d.)) (Fig. 10).

c) Laser processing for surface property enhancement

Table 1 Comparative evaluation of friction measurement and analysis methods in metal forming

Method	Accuracy	Main Limitations	Application Range	Representative References
Pin-on-Disk/Pin-on-Plate	Moderate–High under controlled conditions	Simplified contact geometry; limited representation of real forming stresses and material flow	Material screening, lubricant comparison, wear mechanism analysis	Di Puccio et al., 2024; Salguero et al., 2025; Velkavrh et al. 2025; Trzepiecinski and Lemu 2020)
Ring Compression Test	High for bulk forming friction estimation	Sensitive to geometry, alignment, and calibration curves; limited for complex stress states	Forging, extrusion, high-pressure bulk metal forming	Real-Time Quality Monitoring of Laser Cladding Process on Rail Steel by an Infrared Camera (n.d.); Effects of Coating and Lubrication on Friction and Wear for Metal-to-Metal Application Request PDF. 2024; Investigation on blasted tool surfaces as a measure for material flow control in sheet-bulk metal forming. 2024; An alternative evaluation method for friction condition in cold forging by ring with boss compression test. 2024)
Stretch Forming Test	High for sheet metal forming	Restricted to sheet materials; requires optical measurement systems	Deep drawing, stamping, lubrication and surface finish evaluation	Investigation on blasted tool surfaces as a measure for material flow control in sheet-bulk metal forming. 2024; An alternative evaluation method for friction condition in cold forging by ring with boss compression test. 2024; Domitner et al. 2021)
Strip Drawing Test	High at tool–sheet interface	Edge effects; simplified contact conditions	Sheet metal forming, coating and lubricant assessment	Sigvant et al. 2019; Trzepiecinski and Lemu 2020; Domitner et al. 2021)
Tribometers (MFT, advanced tribometers)	Very High	High cost; laboratory-scale simulation	Multi-axial loading, elevated temperature forming, industrial condition simulation	An alternative evaluation method for friction condition in cold forging by ring with boss compression test. 2024; Petre et al. 2025; Ramalho & Vilhena, 2025; G. A. Team (n.d.)
High-Speed Tribological Tests	Moderate–High	Difficult isolation of thermal effects; debris influence	High-speed forming, dry and boundary lubrication	Pereira et al. 2024; Huang and Wu (n.d.)
Infrared Thermography-Assisted Experiments	High thermal accuracy	Emissivity calibration; limited micro-scale resolution	Friction-induced heat analysis, extrusion and high-speed forming	Infrared thermography for monitoring heat generation in a linear friction welding process of Ti6Al4V alloy Request PDF. 2024; Rangel et al. (n.d.); Kisuka et al. 2025); Thermal Characteristic Analysis and Experimental Study of a Spindle-Bearing System (n.d.); Wu and Tan (n.d.)
Finite Element Method (FEM) with Experimental Calibration	Very High (when validated)	Strong dependence on material and friction models	Process optimization, prediction of friction, heat generation, tool wear	Study of Tool Wear in Friction Stir Processing of Metal Matrix Composites—A Review (n.d.); Mia et al. 2025; Anggono et al. (n.d.); Tang et al. 2018)
Molecular Dynamics (MD) Simulations	Very High at nanoscale	Computationally intensive; limited length/time scales	Nanoscale friction, interface and coating mechanism studies	Kheiri and Tsukanov 2023; Yeo and Jang 2010; Ru et al. 2024)
AI/Machine Learning-Assisted Models	Emerging, potentially Very High	Requires large datasets; limited industrial validation	Predictive tribology, smart forming processes, digital twins	Kurdi et al. 2020; Mishra et al. 2024)

Laser processing techniques such as laser hardening, remelting, glazing, alloying, cladding, shock peening, and texturing are employed to enhance surface properties. These methods address limitations found in conventional techniques, such as weak bonding strength and porosity. Laser treatments can improve hardness and wear resistance by precisely modifying the surface without significantly affecting the bulk material properties (Arulvel et al. 2023; Yao et al. 2022; Tan et al. (n.d.); Karimi et al. (n.d.)) (Fig. 11).

d) Magnetic field-assisted plasma spraying

A novel approach combines transverse static magnetic fields with supersonic plasma spraying to produce Ni-based coatings with enhanced properties. The application of a magnetic field during the spraying process results in coatings with reduced porosity increased residual compressive stress, and improved microhardness. This technique also influences the distribution of hard phases within the coating, leading to superior tribological performance (Wang et al. 2022a, 2022b; Zhou et al. (n.d.); Hu et al. (n.d.)). Understanding and implementing these advanced surface treatment techniques are essential for optimizing the performance of components in various forming processes (Fig. 12).

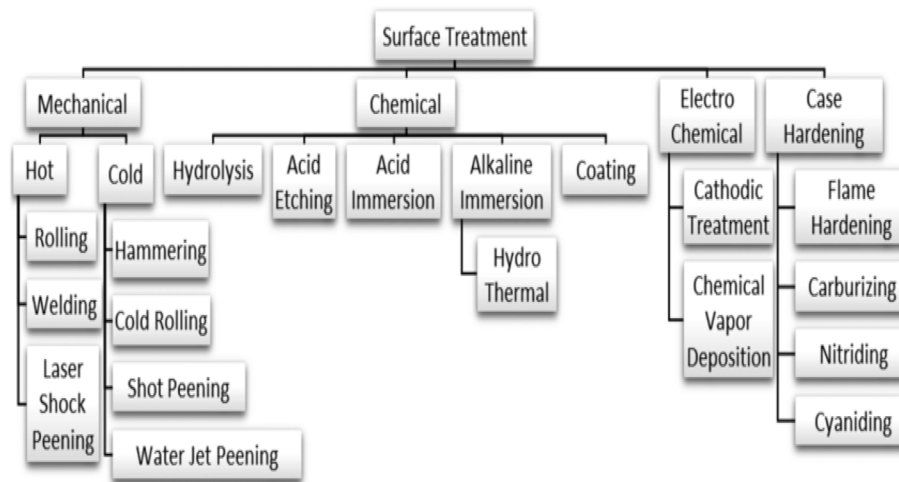


Fig. 8 Classifications of surface treatment process (A review on peening processes and its effect on surfaces | Request PDF. 2024)

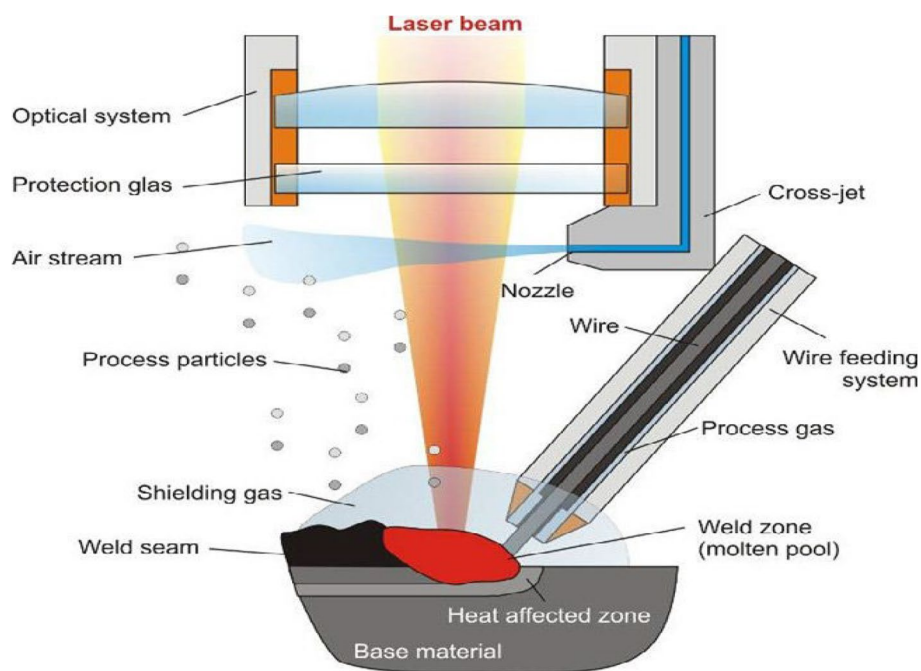


Fig. 9 Principle of the laser cladding process (Flexible scanner-based laser surface treatment (n.d.))

Surface treatment in drawing

In metal drawing, surface finish significantly affects the friction between the die and the workpiece, impacting the drawing force and final product quality. Proper surface treatments can reduce defects such as scratches and tool marks. Lubrication is a common method to minimize friction, but the die's surface roughness also plays a crucial role. Studies indicate that optimizing die surface roughness can enhance material flow and reduce drawing forces (Karunathilaka et al. (n.d.); Padmanabhan et al. (n.d.)).

Surface treatment in sheet metal forming

Sheet metal forming processes, including deep drawing and stamping, are sensitive to friction conditions at the tool-workpiece interface. Surface engineering techniques, such as Physical Vapor Deposition (PVD) coatings, have been developed to improve tribological performance in these applications. Additionally, the surface roughness of stamping dies influences simulation results and the accuracy of forming process predictions. Careful material selection, precise die design, and appropriate lubrication techniques are necessary to prevent surface defects and ensure smooth metal deformation during the deep

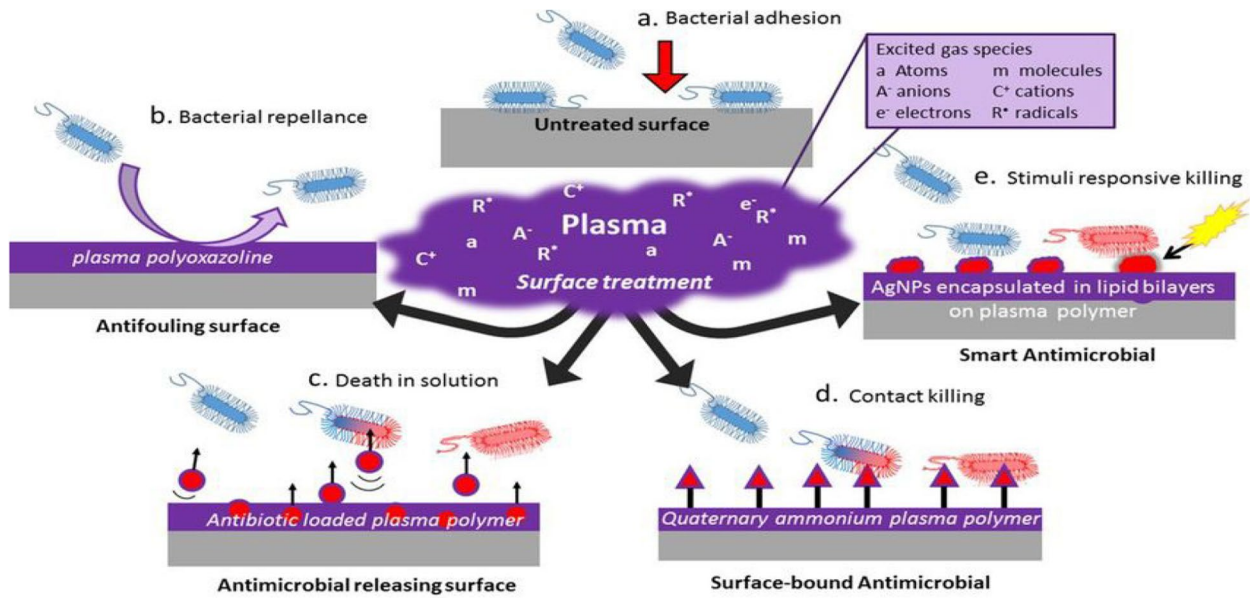


Fig. 10 a A schematic showing plasma surface treatment facilitating the generation of the four classes of antibacterial strategies: **b** antifouling surface, **c** antimicrobial-releasing surface, **d**. surface-bound antimicrobial and **e** smart, stimuli-responsive antimicrobial surface (PDF) 2024)

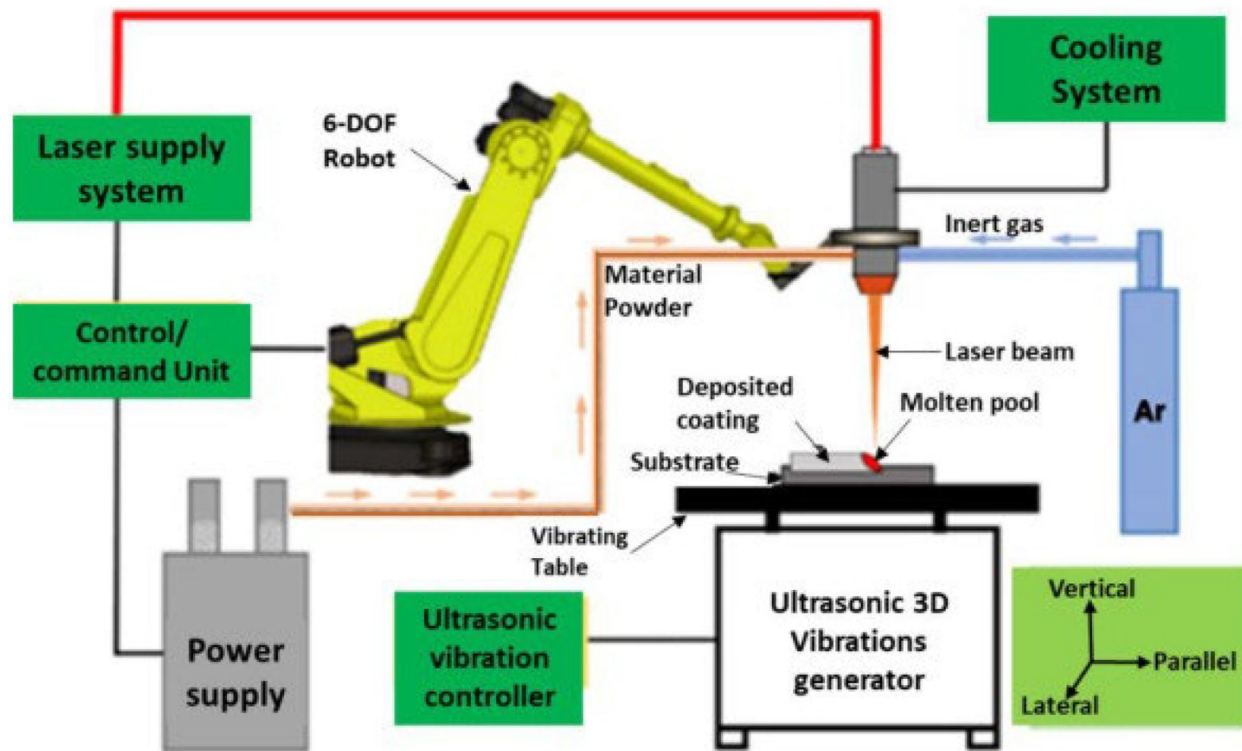


Fig. 11 Laser Processing for Surface Property Enhancement (Arulvel et al. 2023)

drawing process (Sigvant et al. 2019; Trzepieciński 2023; Sivarajan and Padmanabhan 2018; Carlsson et al. (n.d.)).

Surface treatment in extrusion

In extrusion processes, die surface treatments are crucial for achieving the desired surface quality and dimensional

accuracy of extruded products. Surface roughness and die wear significantly affect the extrusion process's efficiency and the final product's quality. Research has shown that surface treatments like nitriding can enhance die durability and reduce wear. Additionally, optimizing extrusion parameters and employing post-processing

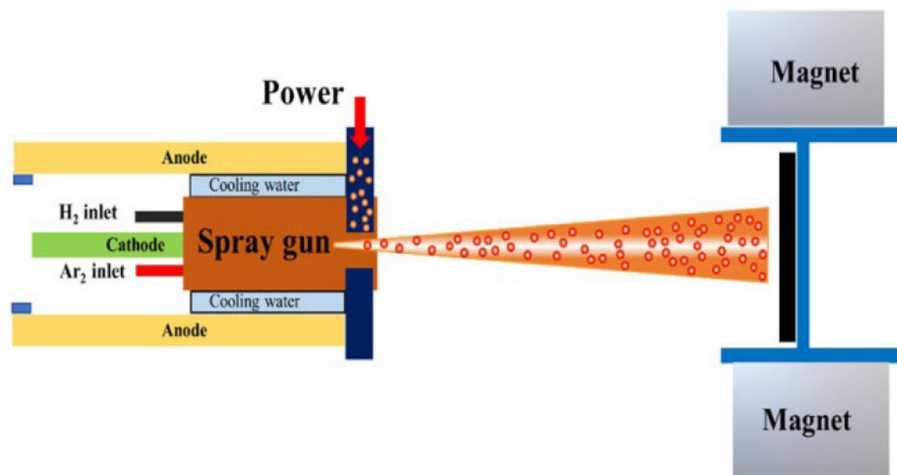


Fig. 12 Transverse static magnetic field-assisted supersonic plasma spraying device (Wang et al. 2022a)

techniques can improve the surface finish of extruded components (Sukindar et al. 2024; Leśniak et al. 2024; Gupta and Taufik 2021).

Surface treatment in hot and cold forging

Forging dies are subjected to extreme pressures and temperatures, leading to wear mechanisms such as abrasion, adhesion, and thermal fatigue. Surface treatments like nitriding and the application of hard coatings can enhance die life and performance. In cold forging, new surface processes have been developed to substitute environmentally hazardous lubricants, improving both performance and environmental impact. Additionally, heat treatment methods, such as normalizing and stress relief (NSR), have been shown to improve the mechanical properties of cold-forged steel, offering similar benefits to traditional spheroidizing annealing (SA) with reduced processing time (Dubar et al. 1998; Lim et al. 2025).

Methods and comparative analysis of surface treatment methods for metal forming processes

Surface treatment of forming processes plays a vital role in enhancing the performance, durability, and efficiency of materials involved in manufacturing. These treatments are designed to improve the surface properties of metals, polymers, and other materials to withstand wear, corrosion, and high-stress conditions during forming operations.

Table 2 provides a comparative overview of key surface treatment techniques, highlighting their suitability for different forming applications, trade-offs in performance, and practical limitations.

Discussion and future perspectives

The evaluation of friction in metal forming relies on a diverse set of experimental, numerical, and data-driven approaches. As summarized in Table 1, each method

presents distinct advantages and limitations, with no single technique fully capturing the complex tribological interactions at the tool–workpiece interface. The selection of an appropriate method is highly dependent on the specific forming process, material properties, and operational conditions.

Simplified laboratory tests, such as pin-on-disk or pin-on-plate, are effective for preliminary screening of materials and lubricants but often fail to replicate the high contact pressures and complex strain paths encountered in actual forming operations. In contrast, process-simulative tests like ring compression and strip drawing offer closer approximations of industrial conditions, though they are sensitive to specimen geometry and require careful calibration. Advanced tribometers (e.g., MFT systems) provide precise control over load, speed, temperature, and lubrication, effectively bridging laboratory studies and industrial reality, albeit at higher cost. Infrared thermography enables valuable insights into frictional heating but is constrained by challenges in emissivity calibration and spatial resolution.

Numerical methods, particularly Finite Element Method (FEM) simulations, serve as powerful complements to experiments, enabling prediction of friction, heat generation, and wear across complex geometries. However, their accuracy is contingent on reliable input data and validated constitutive models. At the atomic scale, molecular dynamics (MD) simulations elucidate fundamental interfacial mechanisms but remain limited by computational expense and scale. Emerging data-driven techniques, including artificial intelligence (AI) and machine learning (ML), show considerable promise for real-time friction prediction and the development of digital twins, though they depend on the availability of extensive, high-quality datasets and require rigorous industrial validation.

Table 2 Comparative analysis of surface treatment methods for metal forming processes

Method	Key Advantages	Main Limitations	Typical Applications	Representative Refs
Laser Cladding	High bonding strength, minimal dilution, precise control, improved hardness and wear resistance	High equipment cost, thermal distortion risk, requires skilled operation	Die & mold repair, hot forging/press forming dies, high-wear components	Norhafzan et al. 2021; Zhao et al. 2023; Norhafzan et al. (n.d.); Zhong et al. 2025; Flexible scanner-based laser surface treatment (n.d.)
Plasma Surface Treatment	Environmentally friendly, enhances adhesion, suitable for polymers/metals/textiles	Surface effect may degrade over time, batch processing limitations	Adhesion promotion, pre-treatment for coatings, biomedical surfaces	Plasma activation. 2023; Haji and Kan (n.d.); Kim et al. 2025; Hegemann et al. (n.d.); PDF 2024)
Laser Processing (Hardening/Texturing)	Non-contact, high precision, localized treatment, improved tribological properties	Limited to line-of-sight, high initial investment	Tool surface hardening, friction reduction via texturing, aerospace components	Arulvel et al. 2023; Yao et al. 2022; Tan et al. (n.d.); Karimi et al. (n.d.)
PVD Coatings	Excellent wear/corrosion resistance, low friction, wide material variety	Line-of-sight process, thin coating thickness, substrate temperature sensitivity	Sheet metal forming dies, cutting tools, extrusion dies	Sigvant et al. 2019; Trzepieciński 2023; Siv- arajan and Padmanabhan 2018; Carlsson et al. (n.d.)
Nitriding	Improved surface hardness, fatigue strength, good wear resistance at high temps	Brittle white layer formation, process time-consuming, limited to specific steels	Forging dies, extrusion tools, gears and bearings	Sukindar et al. 2024; Leśniak et al. 2024; Gupta and Taufik 2021)
Magnetic Field-Assisted Plasma Spraying	Reduced porosity, improved coating adhesion, enhanced micro hardness	Complex setup, limited scalability, high cost	High-performance coatings for severe environments, specialized tooling	Wang et al. 2022a; Wang et al. 2022b; Zhou et al. (n.d.); Hu et al. (n.d)

Looking forward, the field of metal forming tribology is poised to evolve through several key avenues:

1. **Multi-scale and Hybrid Methodologies:** Future research should integrate MD simulations, FEM, and real-time experimental data (e.g., from infrared thermography or digital image correlation) to create holistic, multi-scale models that connect atomic-scale interactions with macroscopic forming behavior.
2. **AI and Data-Driven Tribology:** The application of AI and ML will expand for predictive maintenance, optimization of surface treatment parameters, and the creation of adaptive process controls. Success in this area hinges on building comprehensive tribological databases.
3. **Sustainable and Bio-Inspired Solutions:** Increasing environmental concerns will drive innovation in eco-friendly lubricants (e.g., bio-based oils), bio-inspired surface textures for drag reduction, and green surface engineering techniques such as plasma electrolytic oxidation.
4. **Advanced Materials and Smart Coatings:** Development will focus on nanostructured and multilayer coatings, smart surfaces with stimuli-responsive properties, and high-entropy alloy (HEA) coatings, all aimed at achieving superior wear resistance and tunable friction under extreme conditions.
5. **Standardization and Technology Transfer:** There is a critical need for standardized testing protocols that

better replicate industrial conditions. Furthermore, concerted efforts to bridge the gap between academic research and industrial application—through collaborative projects and pilot-scale demonstrations are essential for the widespread adoption of advanced tribological solutions.

In summary, the advancement of metal forming processes requires a convergent strategy that synergizes accurate experimental characterization, robust multi-scale modeling, intelligent data analytics, and innovative, sustainable surface engineering. By pursuing these integrated research directions, significant improvements in process efficiency, tool longevity, and product quality can be realized.

Conclusion

Friction remains a fundamental parameter in metal forming processes, exerting a profound influence on material flow behavior, tool life, surface integrity, and overall process stability. This review highlights the progression and refinement of experimental techniques including pin-on-disk testing, ring compression, stretch forming, and advanced tribometric methods each contributing to a more comprehensive understanding of frictional interactions under varying operational conditions. The incorporation of real-time measurement technologies and the integration of empirical data with Finite Element Method (FEM) simulations have significantly enhanced the predictive capabilities for process optimization. Key parameters such as temperature, sliding velocity, lubrication

type, and contact pressure are shown to critically affect frictional behavior and associated thermal and mechanical effects. Future advancements in experimental methodologies and data-driven modeling approaches are essential for achieving greater precision, efficiency, and tool longevity in modern metal forming operations.

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Data availability

All data that support the findings of this study are included in the article. If any supplementary files needed to support this study are available on request from the corresponding author upon reasonable request.

Declarations

Competing interests

Dear editors, we confirm that there are no conflicts of interest associated with this review research. We appreciate your consideration of the manuscript for publication in your journal and look forward to your response.

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