

Influence of Lubricants on the Surface Quality of Incrementally Formed Parts: A Review

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Abstract - Incremental Sheet Forming (ISF) is an advanced dieless sheet metal forming process that offers high flexibility for manufacturing complex geometries, making it suitable for prototype development and low-volume production. The integration of industrial robots into ISF, known as Robot-Assisted Incremental Sheet Forming (RAIF), has further enhanced the process by providing a larger working envelope, improved flexibility, and cost-effective manufacturing compared with conventional CNC-based systems. However, continuous sliding contact between the forming tool and the sheet material generates friction, adhesion, and tool wear, which significantly influence the surface quality of the formed components. Appropriate lubrication is therefore essential to reduce friction, minimize tool wear, prevent galling, and improve surface finish. This review presents a comprehensive overview of the influence of lubricants on the surface quality of incrementally formed parts. Various lubrication strategies, including conventional industrial lubricants, cutting oils, hydraulic oils, solid lubricants, and environmentally friendly vegetable-based lubricants, are critically reviewed with respect to their tribological performance and their effects on surface roughness, friction, and tool wear. The advantages and limitations of industrial and bio-based lubricants are discussed to highlight their suitability for sustainable manufacturing. The review also identifies current research trends and gaps, particularly the limited studies on eco-friendly lubricants in Robot-Assisted Incremental Sheet Forming, and outlines future directions for developing sustainable lubrication strategies to improve the surface quality and efficiency of incrementally formed parts.

Key Words: Incremental Sheet Forming, Robot-Assisted Incremental Sheet Forming, Lubrication, Surface Quality, Surface Roughness, Tribology, Industrial Lubricants, Bio-Based Lubricants, Sustainable Manufacturing.

1. INTRODUCTION

Sheet metal forming is one of the most widely used manufacturing processes for producing components with complex geometries in industries such as automotive, aerospace, biomedical, shipbuilding, and consumer products. Conventional sheet metal forming processes, including deep drawing, stamping, bending, and stretch forming, require dedicated dies and punches, making them economical only for mass production. The high tooling cost, long lead time, and limited flexibility of these conventional methods restrict their suitability for prototype development and customized manufacturing. The increasing demand for rapid product development and low-volume production has led to the development of flexible forming technologies that eliminate the need for dedicated tooling.

Incremental Sheet Forming (ISF) is a dieless sheet metal forming process in which a hemispherical forming tool gradually deforms a clamped sheet along a predefined tool path until the desired geometry is achieved. The process offers significant advantages, including reduced tooling cost, shorter development time, greater design flexibility, and the ability to manufacture complex parts with customized geometries. Owing to these benefits, ISF has attracted considerable attention from both researchers and industries as an alternative to conventional forming techniques.

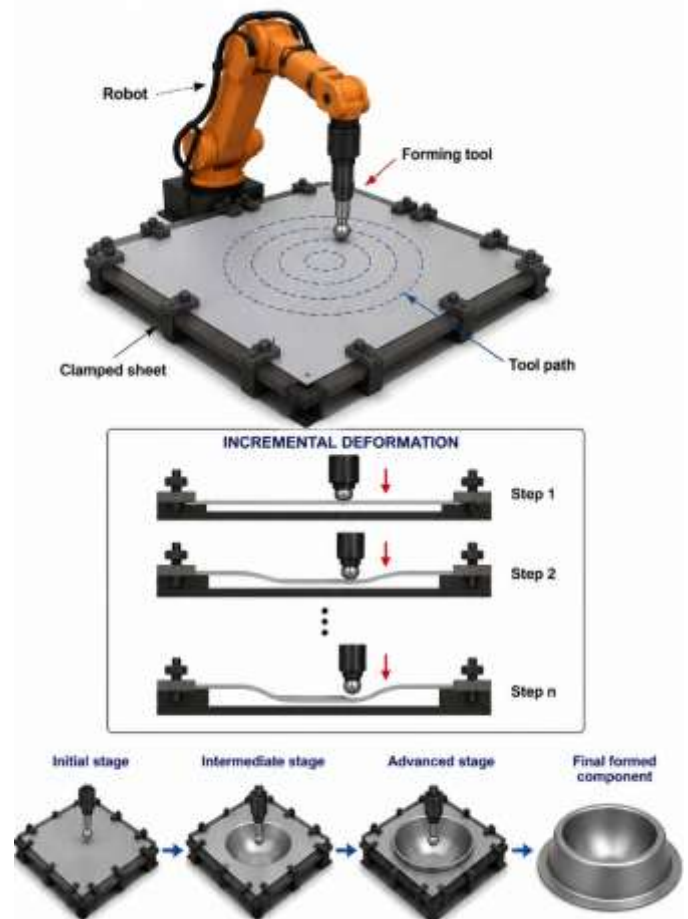


Fig -1: Schematic representation of the Incremental Sheet Forming (ISF) process.

In recent years, the use of industrial robots has led to the development of Robot-Assisted Incremental Sheet Forming (RAIF). Compared with conventional CNC-based systems, industrial robots provide a larger working envelope, improved flexibility, lower capital investment, and greater adaptability for manufacturing large and complex components. These

advantages have made RAIF a promising technology for prototype manufacturing, customized products, and small-batch production. Despite its advantages, the repeated sliding contact between the forming tool and the sheet material during incremental forming generates friction, adhesion, and tool wear, which significantly influence the surface quality of the formed component. Excessive friction can result in higher forming forces, galling, surface scratches, increased tool wear, and poor surface finish. Therefore, maintaining effective lubrication at the tool-sheet interface is essential for reducing friction, improving tribological performance, and enhancing the surface integrity of incrementally formed parts. Various lubrication strategies have been investigated to improve the forming performance of ISF, including mineral oils, gear oils, cutting fluids, hydraulic oils, solid lubricants, and synthetic lubricants. However, most conventional industrial lubricants are petroleum-based and pose environmental and disposal challenges. In response to increasingly stringent environmental regulations and the growing emphasis on sustainable manufacturing, researchers have focused on biodegradable and renewable vegetable-based lubricants such as coconut oil, mustard oil, soybean oil, sunflower oil, and castor oil. These bio-based lubricants possess excellent lubricity, high biodegradability, low toxicity, and good boundary lubrication characteristics, making them promising alternatives to conventional industrial lubricants.

This review aims to present a comprehensive overview of the influence of lubricants on the surface quality of incrementally formed parts. The paper reviews the tribological aspects of Incremental Sheet Forming, discusses the performance of conventional industrial and environmentally friendly bio-based lubricants, and summarizes their effects on friction, tool wear, and surface roughness. Furthermore, the review identifies current research trends and existing knowledge gaps, particularly in the application of sustainable lubricants for Robot-Assisted Incremental Sheet Forming, and highlights future research directions for improving surface quality while promoting environmentally responsible manufacturing practices.

2. LUBRICATION IN INCREMENTAL SHEET FORMING

Lubrication plays a crucial role in the Incremental Sheet Forming (ISF) process by controlling the tribological interaction between the forming tool and the sheet material. During ISF, the forming tool follows a programmed tool path while applying localized pressure to the clamped sheet, resulting in continuous sliding contact throughout the forming operation. This repeated interaction generates friction, heat, and material adhesion, which can adversely affect the surface quality, dimensional accuracy, and tool life if adequate lubrication is not provided. An effective lubricant forms a protective film at the tool-sheet interface, reducing direct metal-to-metal contact, minimizing wear, and improving the quality of the formed component. Consequently, lubricant selection has become one of the most important factors influencing the performance and reliability of Incremental Sheet Forming, particularly in Robot-Assisted Incremental Sheet Forming (RAIF), where long tool paths and continuous forming cycles demand consistent lubrication.

2.1 Role of Lubrication

The performance of the incremental forming process largely depends on the tribological conditions developed at the contact interface between the forming tool and the sheet material. During deformation, the hemispherical forming tool continuously slides over the sheet surface while applying localized compressive forces. In the absence of adequate lubrication, direct contact between the two metallic surfaces increases friction, resulting in higher forming forces, excessive heat generation, and deterioration of the surface finish.

Friction is one of the primary factors governing the quality of incrementally formed parts. Excessive friction restricts smooth tool movement and increases resistance to deformation, leading to non-uniform material flow and higher energy consumption. Furthermore, high friction promotes adhesion, in which microscopic fragments of the sheet material adhere to the tool surface. The accumulated adhered material subsequently scratches the sheet surface during continued forming, producing irregular tool marks and increasing surface roughness. Under severe contact conditions, adhesion may further develop into galling, a form of adhesive wear characterized by material transfer between the contacting surfaces. Galling significantly degrades the surface quality of the formed component and accelerates tool deterioration. Continuous friction and adhesive wear also contribute to tool wear, altering the geometry and surface condition of the forming tool, which ultimately affects dimensional accuracy and process consistency. Proper lubrication effectively minimizes these tribological problems by reducing friction, suppressing adhesion and galling, lowering tool wear, and maintaining a stable contact condition throughout the forming process. As a result, smoother tool movement is achieved, leading to improved surface finish and enhanced quality of incrementally formed parts.

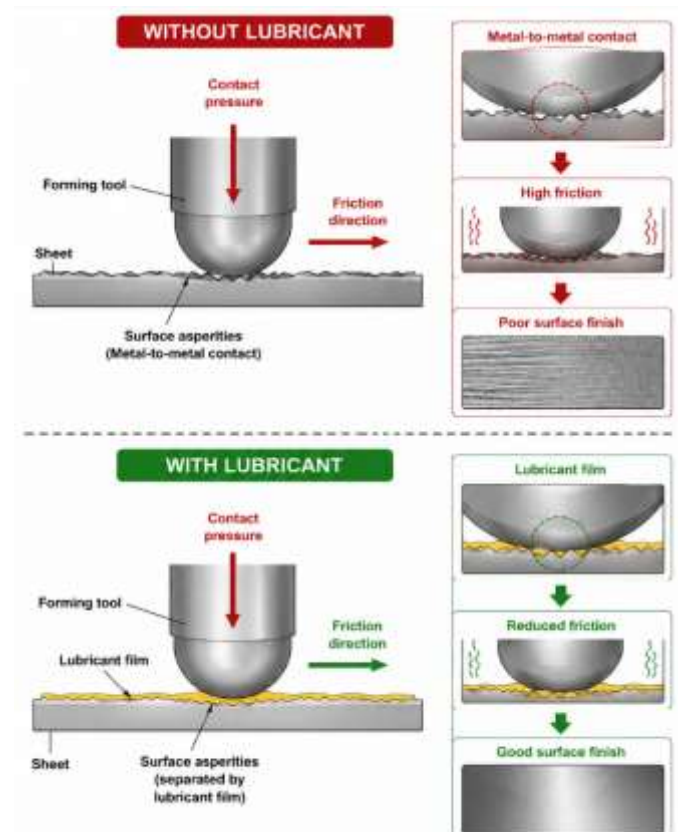


Fig -2: Role of Lubricant at tool sheet interface during ISF

2.2 Lubrication Mechanisms

The effectiveness of a lubricant during Incremental Sheet Forming depends on its ability to establish and maintain a lubricating film between the tool and the sheet material. Depending on the operating conditions, three primary lubrication mechanisms are encountered: boundary lubrication, mixed lubrication, and hydrodynamic lubrication.

Boundary lubrication is the predominant lubrication mechanism in Incremental Sheet Forming because of the high contact pressures and relatively low sliding speeds involved in the process. Under these conditions, the lubricant forms a thin molecular film that adheres to the contacting surfaces and prevents direct metal-to-metal contact. Vegetable-based lubricants are particularly effective in boundary lubrication due to the presence of polar fatty acid molecules, which strongly adsorb onto metallic surfaces and reduce adhesive wear. In mixed lubrication, the load is shared between the lubricant film and the surface asperities. Although partial metal-to-metal contact still exists, the lubricant significantly reduces friction and wear by separating a large portion of the contacting surfaces. Mixed lubrication may occur during transitional stages of incremental forming where contact pressure and sliding conditions vary.

Hydrodynamic lubrication occurs when a continuous lubricant film completely separates the tool and sheet surfaces, thereby eliminating direct contact. This mechanism is generally associated with high sliding speeds and relatively low contact pressures. Since Incremental Sheet Forming operates under localized deformation with high normal loads, complete hydrodynamic lubrication is rarely achieved. Nevertheless, lubricants with appropriate viscosity and good film-forming capability help maintain a stable lubricating layer that minimizes friction and improves surface quality.

The formation and stability of the lubricant film are influenced by several factors, including lubricant viscosity, chemical composition, thermal stability, surface roughness of the contacting materials, contact pressure, and sliding speed. Lubricants capable of retaining a continuous and durable film under severe forming conditions provide better tribological performance by reducing friction, preventing adhesive wear, minimizing tool degradation, and producing superior surface quality. Consequently, understanding lubrication mechanisms is essential for selecting suitable industrial and environmentally friendly lubricants for improving the performance of Incremental Sheet Forming processes.

3. TYPES OF LUBRICANTS USED IN ISF

The performance of Incremental Sheet Forming (ISF) is strongly influenced by the type of lubricant used at the tool-sheet interface. An effective lubricant minimizes friction, reduces adhesive wear, prevents galling, and improves the surface quality of the formed component. The selection of a lubricant depends on its viscosity, chemical composition, load-carrying capacity, thermal stability, environmental impact, and ability to maintain a stable lubricating film under localized deformation.

3.1 Industrial Lubricants

Industrial lubricants are the most commonly used lubricants in Incremental Sheet Forming because of their excellent load-carrying capacity, thermal stability, and availability. Various mineral oils, gear oils, hydraulic oils, cutting oils, and extreme-pressure (EP) lubricants have been

employed to reduce friction and improve the surface finish of incrementally formed parts.

Gear oils possess high viscosity and superior film strength, enabling them to maintain a stable lubricating layer under the high contact pressures encountered during incremental forming. Their extreme-pressure additives improve load-carrying capacity and reduce adhesive wear, making them suitable for severe forming operations.

Hydraulic oils contain anti-wear, anti-oxidation, and corrosion-inhibiting additives that provide stable lubrication and good thermal resistance. These lubricants reduce friction and maintain process stability during prolonged forming operations, although they are primarily formulated for hydraulic systems rather than forming applications.

Cutting oils are specifically developed for metalworking operations and contain sulphur-, chlorine-, and phosphorus-based extreme-pressure additives. These additives chemically react with metallic surfaces under high pressure, reducing adhesion, minimizing tool wear, and improving surface finish. Consequently, cutting oils have been widely reported as effective lubricants for incremental sheet forming.

Mineral oils are economical and widely available; however, their lubrication performance depends largely on viscosity and additive formulation. Under severe contact conditions, conventional mineral oils may experience lubricant film breakdown, resulting in increased friction and surface deterioration.

Extreme-pressure (EP) lubricants have been extensively investigated for forming difficult-to-form materials such as titanium and stainless steel. Hussain et al. reported that molybdenum disulfide (MoS_2)-based grease significantly reduced tool adhesion and improved the surface quality of commercially pure titanium sheets during incremental forming. Similarly, Bay et al. demonstrated that lubricants containing extreme-pressure additives exhibit superior anti-galling characteristics compared with conventional mineral oils, particularly under high contact pressures.

Despite their excellent tribological performance, conventional industrial lubricants are predominantly petroleum-based and present several limitations, including poor biodegradability, disposal challenges, and potential environmental hazards. Increasingly stringent environmental regulations have therefore encouraged the search for sustainable alternatives.

3.2 Vegetable-Based Lubricants

Growing environmental awareness has accelerated research into biodegradable lubricants derived from renewable resources. Vegetable oils have emerged as promising alternatives to petroleum-based lubricants because they possess high lubricity, excellent biodegradability, low toxicity, and superior boundary lubrication characteristics. Their performance is largely attributed to the presence of polar fatty acids that readily adsorb onto metallic surfaces and form a stable lubricating film.

Among the various bio-lubricants investigated, Coconut Oil has demonstrated excellent tribological performance owing to its high lauric acid and triglyceride content, which provides strong boundary lubrication and reduces adhesive wear. Mustard Oil, rich in oleic and erucic acids, also exhibits good lubricating characteristics by forming a protective molecular film between the contacting surfaces.

Other vegetable oils, including Soybean Oil, Sunflower Oil, Palm Oil, and Castor Oil, have also been investigated for

metal forming applications. These oils contain long-chain fatty acids that improve lubricity and reduce friction while offering excellent biodegradability and renewability. Castor oil possesses comparatively higher viscosity, providing strong lubricant film formation, whereas sunflower and soybean oils are valued for their balanced viscosity and good oxidation characteristics. Palm oil has also been reported as an effective lubricant because of its high oxidative stability and excellent load-carrying capacity.

Several researchers have reported that vegetable-based lubricants can produce surface finishes comparable to those obtained using conventional industrial oils while significantly reducing environmental impact. However, their relatively lower oxidation stability and thermal resistance may limit their performance under severe forming conditions. Consequently, current research is focused on improving vegetable oils through chemical modification and the incorporation of performance-enhancing additives to increase their industrial applicability.

3.3 Solid Lubricants

Solid lubricants are employed in Incremental Sheet Forming when conventional liquid lubricants fail to withstand high contact pressures or elevated temperatures. Unlike liquid lubricants, solid lubricants form a durable protective layer on the contacting surfaces, reducing friction and preventing direct metal-to-metal contact.

Among the available solid lubricants, Molybdenum Disulfide (MoS_2) is one of the most widely used because of its layered crystal structure, which provides excellent load-carrying capacity and low friction under boundary lubrication conditions. Graphite is another commonly used solid lubricant that effectively reduces friction due to its lamellar structure, although its performance depends on humidity and operating conditions. Hexagonal Boron Nitride (h-BN) has also gained attention because of its excellent thermal stability, chemical inertness, and low coefficient of friction, making it suitable for high-temperature forming applications.

A significant contribution to this field was made by Hussain et al., who investigated various lubrication strategies for incremental forming of commercially pure titanium sheets. Their study showed that a grease-based MoS_2 paste combined with micro-arc oxidized surface coatings effectively reduced tool adhesion, minimized galling, and significantly improved surface quality compared with conventional mineral oils. Their work demonstrated the importance of selecting appropriate lubrication systems for difficult-to-form materials and established solid lubricants as effective solutions for improving tribological performance in Incremental Sheet Forming.

Overall, the literature indicates that industrial lubricants continue to provide excellent forming performance because of their high load-carrying capacity and thermal stability. However, increasing environmental concerns have encouraged the development of biodegradable vegetable-based lubricants, while solid lubricants remain valuable for applications involving severe tribological conditions. Continued research is directed toward developing sustainable lubrication systems that combine high tribological performance with minimal environmental impact.

4. RESEARCH TRENDS AND RESEARCH GAPS

The increasing demand for lightweight, customized, and low-volume sheet metal components has accelerated research in Incremental Sheet Forming (ISF), particularly in the areas of

surface quality improvement and tribological optimization. Recent studies have primarily focused on optimizing process parameters, including tool diameter, step depth, feed rate, tool rotational speed, and lubrication conditions, to enhance the surface finish and dimensional accuracy of incrementally formed parts. Among these factors, lubrication has received considerable attention because it directly influences friction, tool wear, and the surface integrity of the formed components. Several researchers have demonstrated that effective lubrication reduces adhesive wear, suppresses galling, lowers forming forces, and significantly improves surface roughness.

Another important research trend is the growing emphasis on tribological investigations aimed at understanding the interaction between the forming tool, lubricant, and sheet material. Studies have explored the influence of lubricant viscosity, chemical composition, extreme-pressure additives, and lubricant film stability on the forming process. Conventional industrial lubricants such as cutting oils, gear oils, hydraulic oils, and mineral oils continue to be widely used because of their excellent load-carrying capacity and thermal stability. However, increasing environmental concerns have encouraged researchers to investigate sustainable lubrication strategies using biodegradable and renewable vegetable-based lubricants. Bio-lubricants such as coconut oil, mustard oil, soybean oil, sunflower oil, palm oil, and castor oil have shown promising tribological characteristics due to their high fatty acid content, excellent boundary lubrication properties, and biodegradability. These developments support the transition toward environmentally sustainable manufacturing while maintaining satisfactory forming performance.

Despite these advancements, several research gaps remain in the existing literature. Most published studies have been conducted using CNC-based Single Point Incremental Sheet Forming (SPIF) systems, whereas investigations involving Robot-Assisted Incremental Sheet Forming (RAIF) are relatively limited. Although industrial robots offer greater flexibility, larger working envelopes, and lower manufacturing costs, their tribological behaviour under different lubrication conditions has not been extensively investigated.

Furthermore, only a limited number of studies have directly compared the performance of conventional industrial lubricants and vegetable-based lubricants under identical forming conditions. Such comparative investigations are essential for evaluating the feasibility of replacing petroleum-based lubricants with environmentally friendly alternatives without compromising surface quality. In addition, comprehensive tribological studies on aluminium alloys under different lubrication conditions remain scarce, despite aluminium being one of the most widely used materials in incremental forming applications.

Another significant gap is the limited research on the development of environmentally sustainable lubrication strategies specifically for Robot-Assisted Incremental Sheet Forming. Most existing studies primarily evaluate lubricant performance in terms of surface roughness, while comparatively less attention has been given to the combined effects of lubrication on friction, tool wear, lubricant film stability, and long-term process sustainability. Therefore, further investigations are required to establish reliable and eco-friendly lubrication systems capable of improving the surface quality and productivity of incrementally formed parts. Addressing these research gaps will contribute to the advancement of sustainable manufacturing and promote the wider industrial adoption of Robot-Assisted Incremental Sheet Forming.

5. CONCLUSIONS

Lubrication is one of the most critical factors influencing the surface quality and overall performance of Incremental Sheet Forming (ISF). The reviewed literature consistently demonstrates that effective lubrication reduces friction, minimizes adhesion and galling, decreases tool wear, and improves the surface finish of incrementally formed parts. Consequently, appropriate lubricant selection is essential for achieving better product quality and enhanced process reliability. Conventional industrial lubricants, including mineral oils, gear oils, hydraulic oils, and cutting oils, continue to provide excellent tribological performance because of their high load-carrying capacity, thermal stability, and effective extreme-pressure characteristics. However, increasing environmental concerns and stricter sustainability requirements have accelerated research on biodegradable and renewable alternatives. The literature indicates that vegetable-based lubricants, such as coconut oil, mustard oil, soybean oil, sunflower oil, palm oil, and castor oil, possess excellent boundary lubrication characteristics due to their high fatty acid content. Their superior lubricity, biodegradability, low toxicity, and renewable nature make them promising substitutes for conventional petroleum-based lubricants in Incremental Sheet Forming. Despite significant advancements in lubrication research, studies focusing on Robot-Assisted Incremental Sheet Forming (RAIF) remain limited. Most existing investigations have been conducted using CNC-based Single Point Incremental Sheet Forming (SPIF), highlighting the need for systematic research on lubrication strategies specifically for robotic forming systems.

Future research should focus on developing environmentally sustainable lubrication strategies, evaluating advanced bio-based and nano-enhanced lubricants, and optimizing the combined effects of lubricant type and process parameters. Such investigations will contribute to improved surface quality, enhanced process efficiency, and the wider adoption of sustainable manufacturing practices in Incremental Sheet Forming.

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