



Environmentally approach for enhancing tribological characteristics in metal forming: A review

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KEYWORDS	ABSTRACT
Sustainable metal forming Clean forming process Vegetable oil Surface texture Tribological performance Metal forming performance	Vegetable oil is a potential candidate to replace mineral oil-based lubricant because it is renewable and sustainable and also has high biodegradability and low toxicity. The application of surface texture is a clean approach that can be used to improve the lubrication condition of a smooth surface. From tribological tests, researchers found that the friction and wear performances are greatly affected by the physiochemical properties of vegetable oil and the dimension characteristics of texture. Therefore, it is vital to have a detailed understanding of the parameters related to each application. In the metal forming process, it is a relatively new practice to use vegetable oil and surface texture to improve lubrication film thickness at the tool-workpiece interface. These approaches improve the deformation of metal, retard the formation of surface defects and reduce friction, surface roughness and forming load. The quantity of lubricant can be minimised when the thickness of the film between the tool and the material is developed as a boundary lubrication condition. The physical properties of vegetable oil and surface texture are therefore critical and need to be optimised before implementing their use in metal forming work. The present paper reviews the influence of vegetable oil and surface texture on the tribological behaviour in metal forming processes.

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1.0 INTRODUCTION

In general, tribological behaviour of metal forming processes is controlled by many parameters, such as surface texture, load, speed, temperature, lubricants, and material properties (Menezes et al. 2013; Sulaiman et al. 2019). In this article, the authors intend to focus a discussion on the surface texture and lubrication factors only since they are gaining numerous attentions in industry and research areas nowadays. Besides that, these two factors can be considered as environmentally friendly techniques for improving tribological conditions in metal forming (Wahab et al., 2016; Lopez et al. 2019). Practicing sustainable and environmentally friendly techniques have become a major concern in various research fields in the twenty-first century due to the Earth's finite resources and the environment's declining health since the industrial revolution (Razak et al. 2019; Syahrullail et al. 2013a). In 2018, total demand worldwide was 328 Mtoe (million tonnes of oil equivalent), an increase of about 29.13% from 2017 (IEA, 2019). As presented in Figure 1, gas accounted for the highest consumption at 43.6%, followed by renewables, oil, coal and nuclear at 24.7%, 16.5%, 8.2% and 7.01% respectively. This higher energy demand resulted in the increase in a global energy-related carbon dioxide (CO₂) emissions to 33.1 Gt CO₂, which was an increase of nearly 1.7% from the previous year and it was the highest rate of growth since 2013. While the global average annual concentration of CO₂ in the atmosphere was averagely 407.4 ppm, risen by 2.4 ppm since 2017. A major source of CO₂ emission was attributed from industrial sector which ranged from 31.3% to 55.8%.

Environmental awareness in the field of metal forming is, relatively speaking, not a new subject. It was discussed in 1995 by Geiger (1995), who stressed that development of clean forming was of the utmost necessity because all forming productions (pre-treatment, forming, and post-treatment) and semi-finished parts processes yielded huge amounts of unwanted and harmful residual materials and emissions. To implement an environmentally benign tribological system for metal forming, Bay et al. (2010) suggested to use a less harmful lubricants, develop anti-seizure tool materials, surface treatment and coating, and application of structured workpiece and tool surfaces. Besides that, full attention should be given to handling residues in ecologically friendly ways and to reducing consumption of material and energy (Haapala et al., 2013). Apart from that, other factors, such as an increase in raw material prices, occupational disease, industrial policy regarding the environment and reduction of total manufacturing costs have also contributed to the drive towards sustainable manufacturing (Herrmann and Thiede, 2009; Jayal et al., 2010). To assure that current lubricants demonstrated desirable standards of biodegradability, bioaccumulation and toxicity, the US Environmental Protection Agency issued a regulation regarding 'environmentally acceptable lubricants' that dealt with the use and discharge of such lubricants (USEP, 2011).

As proposed by Geiger (1995), a strategy that has been considered in the push toward clean forming is improving conventional tribological or lubricant technology. This is because the reduction of friction between sliding surfaces can reduce energy consumption and emissions. A comprehensive study of passenger cars by Holmberg et al. (2014) revealed that about 33% of total fuel energy was used to overcome friction in transportation. By developing new tribology technology, such friction could be reduced by as much as 14% in the short term between 4 and 8 years. This friction reduction would be possible to save nearly 105,000 million euros and 75,000 million litres of diesel fuel and prevent 200,000 million tonnes of CO₂ from being emitted worldwide. It has been proven that the implementation of sustainable approaches is beneficial not only to the environment but to manufacturers as well. Whereas, in industrial factories, Holmberg and Edemir (2016) postulated that the amount of energy used to overcome friction was

approximately 20%, and they estimated that, by improving the performance of lubrication conditions, about 11% of the total energy used could potentially be saved. Globally, nearly 15–25% of total energy consumption worldwide was used to overcome friction (100 Tera joule/year), and 7000 tonnes of CO₂ emission originated from the work performed to overcome friction

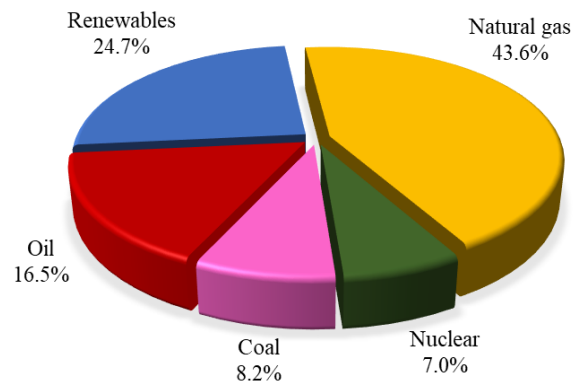


Figure 1: Total energy demand globally 2018 (IEA, 2019).

New tribological technology can be implemented by adopting dry manufacturing or by replacing the currently used mineral-based lubricants with lubricants from nature (Wang, 2004). However, dry manufacturing of a coated layer on the die's surface is not thoroughly environmentally friendly because the process of generating and removing the coated film are harmful to the operator and the environment (Wang, 2004). Therefore, vegetable-based oils are a promising candidate for a new lubricant because they are biodegradable, renewable and less toxic to the environment and have excellent lubricity, a higher viscosity index, a larger load carrying capacity, lower detergency and dispersancy and low volatility (Jabal et al. 2014; Hassan et al. 2016; Sapawe et al. 2016). Nonetheless, vegetable-based oils also have limitations that prevent them from being easily applied in industry: they have high pour points, inconsistent chemical composition, hydrolytic instability, thermal oxidation instability and critical susceptibility to biological degradation (Amiril et al. 2018). Therefore, tremendous amounts of research have been carried out by tribologists and chemists to counteract these limitations so that the Earth's resources can be saved (Syahrullail et al. 2013b; Golshokouh et al. 2014;).

Instead of enhancing the tribological characteristics of the lubricant, similar attention should be given to the tooling system in the metal forming process (Geiger, 1995). This was attributed to the fact of severe frictional occurrence at dies-workpiece interfaces, which resulted in failures due to phenomena like abrasive wear, fatigue and galling. Consequently, these failures would cause the quality of production to deteriorate and would retard the operating lifespan of the tools (Ingarao et al., 2011; Podgornik et al., 2012; Jarfors et al., 2016). In an effort to attain tool material with sufficient toughness and hardness, the development of new chemical compositions has already been effectively investigated. However, this method has a negative impact on the environment as the failed tool becomes scrap and would, thus, augment the amount of discharge waste (Bay et al., 2010). Another approach that meets environmental concerns is mechanical modification on the tool by engraving certain textures on its surface, in which also known as

surface texture. Since the introduction of this technique by Schneider (1984), the influence of surface textures on tribological properties between sliding surfaces has been extensively explored. But their application in the tooling system of metal forming is relatively fresh, being still at the laboratory research stage. Therefore, this paper was designed to give an overview of ongoing research focusing on the application of vegetable-based lubricant oil and surface texture and their simultaneous influence toward metal forming process. Section 2 reviews a chemical modification of vegetable oils and their effect on tribological properties, while Section 3 discusses about physical parameters of the surface texture. Then, Section 4 focuses on the effect of applying surface textures and vegetable oil on the performance of metal forming. Finally, section 5 summarizes the ongoing research and provided a possible future research.

2.0 VEGETABLE OIL

Vegetable oils primarily exist in a form of triglyceride structure, which consist a three-carbon backbone with a long hydrocarbon chain of fatty acids attached to each of the carbons (Giakoumis 2018). Compared to diesel fuel, vegetable oils are renewable, biodegradable, nontoxicity and they have high flash point, viscosity index and lubricity. However, their use in a real application is rather limited due to the poor toleration at elevated temperature condition originated from the present of unsaturated fatty acids or carbon double bonds and β -hydrogen bonds (Reeves et al. 2017). Before being acknowledged as alternative lubricant, the physical characteristics of vegetable oils such as fluidity, viscosity, working temperature range, chemical stability and flammability must be comparable to the existing petroleum-based lubricants. Therefore, chemical modification of natural vegetable oil like esterification, hydrogenation, epoxidation or oligomerisation/estolides are necessity to enhance the drawbacks of the oils (McNutt and He, 2016; Kiu et al. 2017). Esterification or transesterification process involves modification of glycerol ester or fatty acid with the presence of acidic or basic catalyst. Whereas, hydrogenation process is related to the modification of multiple unsaturated fatty acids into single saturated fatty acid through addition of hydrogen atom. In epoxidation process, double bonds of carbon atoms are removed using oxygen atom in order to produce epoxide group or oxirane rings. While, oligomerisation/estolides process served to build attachment between carboxylic acid of one fatty acid with another unsaturated fatty acid. From the experimental investigations, it has been found that physical properties of the modified vegetable oils such as viscosity index, pour point, flash point and oxidation stability are enhanced, as presented in Table 1. It can be seen that after structural modification of natural vegetable oil, viscosity index has improved larger than 200, flash point augment greater than 300°C and pour point value has lowered up to - 40°C, respectively. The improvement in physical properties of the modified vegetable oils suggested that the oils can be exploited at low and high temperature conditions, thus, highly potential to be used as metal forming lubricant.

Various researchers have studied both physical and tribological properties of the modified vegetable oils as, summarized in Table 2. Arumugam and Sriram (2013) utilized chemical modifications of rapeseed oil by conducting epoxidation, hydroxylation and esterification processes. They reported that the synthesized biolubricant only favourable in improving friction properties only. For wear behaviour, a surface contacting with biolubricant was severely worn out and the wear value was 12% greater than the synthetic oil. However, an opposite trend of friction and wear has been discovered in the modified sunflower and castor oil.

Table 1 Physical properties of chemically modified vegetable oils.

Types of chemical modification	Types of vegetable oil	Viscosity		Viscosity index	Pour point (°C)	Flash point (°C)	Oxidation stability
		40°C	100°C				
Esterification/ Transesterification	Jatropha Curcas Oil (Arbain and Salimon, 2010)	79 cP	-	-	-30	>300	-
	Rapeseed oil (Gryglewicz et al., 2013)	7.8	2.7	224	-31.3	-	ΔAc:7.7
	Olive oil emulsion (Bassi et al., 2016)	8.86 mm ² /s	2.76 mm ² /s	182.93	-40	223	-
	Castor oil (Kamalakar et al., 2015)	370.3 cSt	42.83 cSt	171	-36	341	16 (min. RBOT)
	Waste cooking oil (Chowdhury et al., 2014)	32.35 mm ² /s	-	218.47	+1	324.4	1.18 (viscosity 40°C ratio)
	Jatropha oil (Zulkifli et al., 2014)	60.83 cSt	10.21 cSt	156	-35	290	-
Oligomerisation	High-oleic sunflower acid oil	41.94-140.87 mm ² /s	9.51-23.78 mm ² /s	195-218	-	-	-
	Castor oil (García-Zapateiro et al., 2013a)	222-492 mm ² /s	20.32-24.3 mm ² /s	116-155	-	-	-
	Pennycress seed oil (Cermak et al., 2015)	245.8 mm ² /s	33.6 mm ² /s	183	-18	-	-
Hydrogenation	Palm oil (Shomchoam and Yoosuk, 2014)	42.1 cSt	8.7 cSt	192	7	-	22.8 (h)
Epoxidation	Castor oil (Borugadda and Goud, 2014)	35.81 cSt	-	-	8	-	340°C under N ₂ condition -305°C under O ₂ condition TAN = 1.18
	Mustard oil (Kulkarni et al., 2013)	-	-	150-177	-28 to -35	-	-Sludge content: 0.16%
	Cotton seed oil (Zhang et al., 2014)	184.3 mm ² /s	24.7 mm ² /s	166	-6	290	-

For oligomerisation process, García-Zapateiro et al. (2013b) firstly prepared the estolides from sunflower and olive pomace oils before adding separately into sunflower and castor oils. Biolubricant oils synthesized through this method promoted better wear characteristic but deteriorated the frictional performance at low and high sliding speed conditions. In another study, Golshokouh et al. (2013) discovered that jatropha oil demonstrated a good anti-friction ability better than commercial oil when the temperature condition below than 100°C. Exceeding 100°C would trigger deterioration in friction behaviour.

Table 2: Summary of physical and tribological properties of modified vegetable oil.

Type of vegetable oil	Chemical reaction	Physical properties	Tribological performance
Rapeseed oil (Arumugam and Sriram, 2013)	Epoxidation → hydroxylation → esterification	<ul style="list-style-type: none"> - VI reduced from 220 to 160 - Pour point increased until -15°C - Flash point decreased from 320°C to 240°C - Oxidation stability improved by twofold 	<ul style="list-style-type: none"> - COF and frictional force reduced by approximately 23% and 57%, respectively - Wear scar diameter (wsd) increased by 12%
Sunflower and castor oil (García-Zapateiro et al., 2013b)	Oligomerisation	Viscosity of sunflower and castor oil at 10°C enhanced by 322% and 362% respectively	<ul style="list-style-type: none"> - Reduction in wear only - Friction behaviour has deteriorated
Calophyllum Inophyllum (Habibullah et al., 2015)	Transesterification	<ul style="list-style-type: none"> - Highest viscosity index (156) - Flash temperature value of biolubricant higher than paraffin mineral oil but lower than commercial oil. 	<ul style="list-style-type: none"> - WSD lower than paraffin mineral oil but greater than commercial oil - Highest worn surface roughness - Lowest COF value at all test temperature
Rapeseed oil (Liao et al., 2015)	Esterification → Oligomerisation	<ul style="list-style-type: none"> - VI increased greater than 200 - Pour point increased larger than -40°C 	Least wear scar diameter compare with mineral oil and pentaerythritol ester
Palm oil (Zulkifli et al., 2016)	Transesterification	<ul style="list-style-type: none"> - VI enhanced up to 194 	<ul style="list-style-type: none"> - Least COF of about 0.025 - WSD value lower than paraffin but larger than commercial lubricant
Palm oil (Aziz et al., 2016)	Transesterification	<ul style="list-style-type: none"> - VI: 178 - Flash point: 228.5°C - Pour point: -19°C - Cloud point: 6°C 	<ul style="list-style-type: none"> - Lowest COF value - WSD is comparable with commercial oil

Habibullah et al. (2015) produced trimethylpropane (TMP) ester from *Calophyllum Inophyllum* (CI) seed oil and compared its properties with paraffin mineral oil (PMO) and commercial

lubricant. They found that the CI TMP ester possess lowest COF value in all experimental conditions and lowest energy consumption at each temperature from 50°C to 100°C compared with PMO and commercial lubricant. However, wear behaviour of CI TMP biolubricant was better than PMO only and cannot surpassed the performance of commercial lubricant. Similar friction and wear performances have been discovered in palm oil-based lubricant (Zulkifli et al., 2016). Under extreme pressure condition, load carrying capacity of palm oil-based lubricant became superior to PMO. The palm oil-based lubricant was capable to sustain a load until 981 N, while paraffin that could only maintain a load around 788 N only. In contrast, in another study conducted by Liao et al. (2015), neopentyl glycol oligoesters (NOAR) exhibited small WSD value of 0.40mm compared to 0.49 mm of commercial mineral oil-based lubricant. They synthesized NOAR lubricant through multi-step of esterification of rapeseed oil using neopentyl glycol and adipic acid. In addition, load carrying capacity of NOAR was superior to commercial lubricant as it could sustain load up to 784 N, while commercial lubricant cannot bear a load > 431 N.

Aziz et al. (2016) produced three different kinds of lubricants via chemical modification of palm oil, namely pentaerythritol ester (PE), neopentyl glycol ester (NPG) and formulated lubricant (AWCI), and then compared their tribological properties with commercial lubricant. PE and NPG were synthesized from the reaction of palm oil methyl ester with pentaerythritol/neopentyl glycol, while AWCI was produced form the synthesis of PE with anti-wear additives and corrosion inhibitors. From the results presented in Figure 2, only PE (base oil) and AWCI demonstrated enhancement in the frictional performance as their COF values notably declined with temperature rise. Besides that, WSD of AWCI was comparable to commercial lubricant for temperature up to 80°C only, and beyond 80°C AWCI lubricant generated the least WSD values, indicated that wear performance of AWCI is better than commercial lubricant.

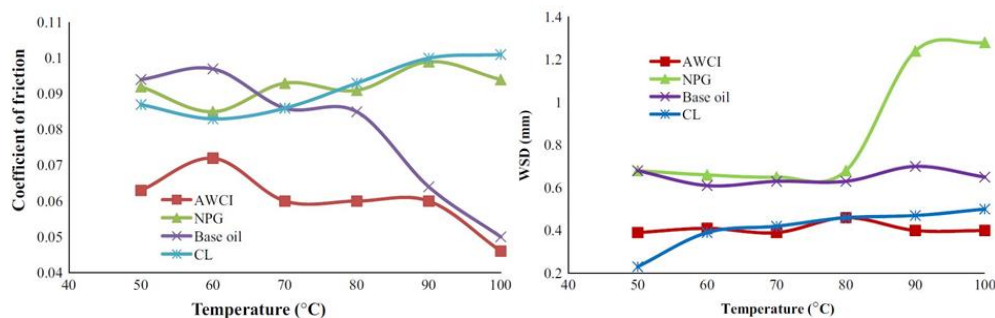


Figure 2: COF and WSD of different lubricants as a function of temperature (Aziz et al., 2016).

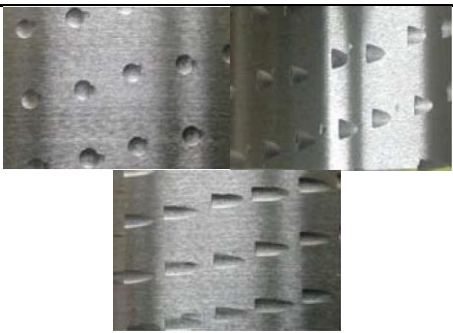
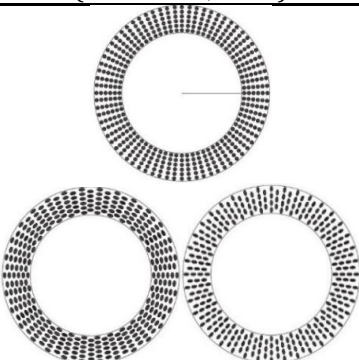
3.0 SURFACE TEXTURE

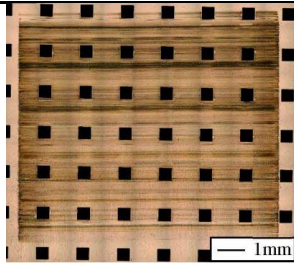
Another clean approach to improve friction and wear performances is by engraving the smooth surface with texture. This approach is considered as one of the environmentally friendly techniques because it does not utilize any chemical reagent during the process and produce minimal waste that has a less impact to the environment (Rao et al. 2019). Several terms have been used by researcher to refer the surface texture such as micropits, dimples, holes, oil pockets and cavities. This surface texture will act as lubricant reservoirs by trapping them and inevitability creating thin film of hydrodynamic lubricant on the upper surface of asperities (Hamilton et al., 1966; Wakuda et al., 2003). At the same time, the surface textures will trap a

metal debris at the interface, hence, improving tribological characteristics (Dumitru et al., 2000). A great number of methods have been used for texturing of smooth surface such as laser surface texturing (Braun et al., 2014), laser machining (Mezzapesa et al., 2013), abrasive jet machining (Wakuda et al., 2003), machining (Zheng et al., 2015), rolling ball indentation (Franzen et al., 2010), marking technique (Nurul and Syahrullail, 2016) and embossing technique (Galda et al., 2009).

The performance of surface texture is greatly affected by its pattern, diameter, depth, arrangement and distribution. Therefore, numerous studies have been dedicated to explore the influence of those parameters on friction and wear characteristics as summarized in Table 3. Wakuda et al. (2003) modified the surface by engraving two different textures of rounded and angular patterns with 100 μm size. The authors implied that the shape or pattern of texture had not so much influenced on friction behaviour because of friction coefficient (COF) of all textured surfaces almost identical with smooth surface. However, the results seemed to contradict with other pattern of surface texture. Pettersson and Jacobson (2003) reported that COF values of groove and quadratic textures were slightly reduced in comparison with the smooth surface. Similar reduction of COF trend also reported by Galda et al. (2009). The authors claimed that the spherical shape and long drop patterns were superior in minimising COF values as compared to the short drop patterns. Their studies emphasized that shape and size of the texture were main parameters that remarkably influenced lubrication condition between metal and metal surfaces.

Table 3: Details of the surface texture by various researchers.

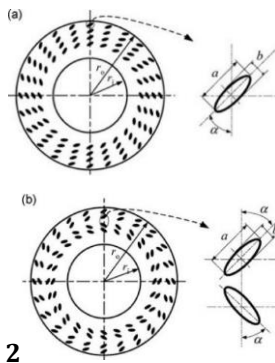
Pattern	Parameter	Results
 <p>(Galda et al., 2009)</p>	<p>Pattern: spherical, short drop, long drop</p> <p>Area density: 7.5% to 20%</p>	<ul style="list-style-type: none"> - Spherical and long drop patterns were superior over short drop in reducing friction - Optimum area density is 20%
 <p>(Qiu and Khonsari, 2011)</p>	<p>Pattern: circular and elliptical</p> <p>Arrangements: elliptical with circumferential and radial orientation</p>	<ul style="list-style-type: none"> - Elliptical pattern gave the lowest COF value - Elliptical dimples with circumferential orientation generated the least COF value compared with radial orientation



(Lu et al., 2016)

Pattern: square
Size: 250x250 μm ,
375x375 μm and
500x500 μm

- Friction reduction effect was independent of dimple size
- Over 10% reduction of friction obtained with textures surface

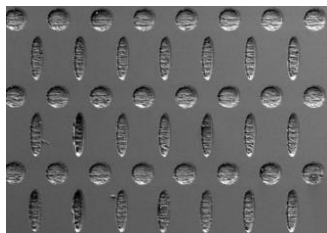


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(Bai and Bai, 2014)

Pattern: elliptical
Arrangements: single-row and double-row

- Friction behaviour strongly dependent on texture distribution
- Double row distributions encouraged vigorous reduction in COF value and temperature rise

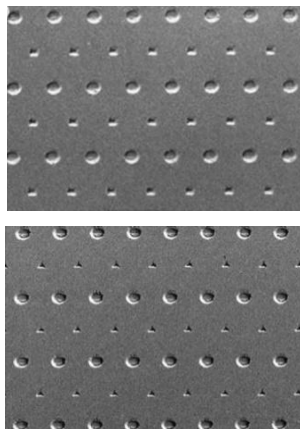


(Segu et al., 2013)

Pattern: Multi textures consist of circle and ellipse

Depth: 3.5 to 7.5 μm
Area density: 7 to 12%

- For depth larger than 5.5 μm , COF trend of 7% and 12% densities behaved contrary to each other.
- Textures with 12% density provided more beneficial effect than 7%.



(Segu and Kim, 2014)

Pattern: multi textures of circle with triangle and circle with square

- Multi textures patterns provided lowest COF value than that of smooth and single pattern surface.

Qiu and Khonsari (2011) engraved three types of texture's pattern on stainless steel specimen using laser marking machine. There are circular, elliptical with circumferentially oriented and elliptical with radial orientation. For the circular shape, the authors investigated the effect of dimple density by varying the diameter. They found that as dimple density increased with diameter, the COF values were substantially reduced. Moreover, Qiu and Khonsari (2011) claimed that type of pattern and its orientation have a remarkable influence on frictional performance. Compared with circular pattern, the elliptical texture provided the least COF value at different load conditions of 4.5 and 8.9 N. Furthermore, the elliptical pattern with circumference orientation gave the lowest COF value than that of radial orientation. Bai and Bai (2014) agreed well with Qiu and Khonsari (2011) that distribution of surface texture significantly affected friction and wear behaviours. Their experimental results reveal that the appropriate textures arrangement or distribution not only beneficial in improving friction and wear properties, but also reduction in heat generation between sliding surfaces. Arrangement of elliptical texture in double-row resulted in reduction of COF value and temperature by 59% and 58%, respectively.

In another investigation, Mezzapesa et al. (2013) focused on exploring the influence of texture's depth on frictional performance by varying the depth from 3.1 μm to 4.2 μm . The results demonstrated that COF value of circular textures experienced continuous reduction trend for depth value ranging from 3.1 μm to 3.9 μm . However, beyond 4.0 μm , the reduction trend vanished and it started to deteriorate because of the COF value became larger than that of COF value of untextured surface. These results indicated that there was an optimum value of texture depth that greatly governed the friction performance. Braun et al. (2014) studied the optimum diameter of round texture by ranging the diameter from 15 to 800 μm . It has been found that the optimum diameter was 40 μm as it gave the maximum reduction of COF value of about 80%. The result was obtained at three different conditions of sliding speed; slow = 50 mm/s, medium = 100 mm/s and fast = 200 mm/s. Larger than 40 μm in diameter, the COF values shortly augmented before continuously fluctuating until 800 μm . Similar study also conducted by Greiner et al. (2015) whose engraved the texture diameter from 20 to 200 μm . Their results exhibited that the optimum diameter of surface texture was between 50 as 75 μm as COF values of both diameter were identical. But, when sliding radius increased from 10 mm to 18 mm, a contradicted trend of COF values as a function of diameter had been observed. By increasing the texture diameter from 50 to 75 μm , the COF value also increased, but beyond 75 μm in diameter the COF values were observed to be continuously declined with diameter. For square texture, Lu et al. (2016) inferred that though utilizing texture decreased the COF value in boundary and mixed lubrication regimes, the size effect did not really significant because of friction of smaller (250 x 250 μm) and large (500 x 500 μm) textures were comparable under all test conditions.

In an attempt to optimize the application of surface texture, Segu et al. (2013) created multi-scale texture dimples on steel AISI 52100 by combining two different patterns of circles and ellipses. They found that the acquired COF value of multi-scale textures was substantially lowered than that of untextured surface. In the extended experiments, Segu and Kim (2014) engraved another two multi-scale textures which consists of circle-triangle pattern and circle-square pattern. The results revealed that both patterns of multi-pattern textures exhibited a remarkable reduction in friction values in comparison with the untextured and single circle-pattern texture. In addition, both multi-pattern textures promoting fastest transition of lubrication film from boundary to mixed regime. Wos et al. (2020) engraved different types of spiral grooves on the spiral disc, namely convergent, dam, both side convergent and both side dam. They found that a spiral disc associated with convergent grooves (one side and both sides) were slightly superior to

those with dam profile in terms of reduction of frictional force. Dan et al. (2020) examined the effect of chevron pattern texture with different percentage of texture density of 5.05%, 9.5%, 13.02% and 15.2%. It was observed that COF was continuously decreased as load and speed increase in all percentage of texture density. At this condition, the optimal density pattern was exhibited by 9.5% chevron texture density. The excessive concentration of surface texture that found in 13.02% and 15.2% led to the large COF and roughness values.

4.0 APPLICATION OF VEGETABLE OIL AND SURFACE TEXTURE IN METAL FORMING

Physical properties of surface texture and their influence on tribological and forming behaviours have been summarized in Table 4. In strip drawing test, Costa and Hutchings (2009) suggested that lubrication condition and plastic deformation of metal were strongly governed by the pattern and orientation of surface texture. The authors concluded that compared with groove textures, die surface consists of circular textures resulted in large friction value than that of smooth surface. This result was attributed by the lower contact area of circular pattern and reduction of stress concentration around the textures. For the factor of texture orientation relative to the forming direction, groove with parallel orientation gave larger friction and drawing force. However, contradict results were obtained once the orientation changed to the perpendicular direction. Costa and Hutchings (2009) highlighted that perpendicular orientation provided thick lubrication film in comparison with parallel direction, consequently improved friction and load properties. These findings had a mutual agreement with the study accomplished by Franzen et al. (2010), where those researchers also not recommended of engraving the texture longitudinally to the drawing direction. Compare to the transverse and zigzag orientation, it was very definite that longitudinal direction resulted in an atrocious striped product as they generated the highest COF and surface roughness values.

Zheng et al. (2015) also investigated the effects of parallel and perpendicular texture orientation on blank holder surface during cold stamping process. Nevertheless, their result was contradicted with the previous studies done by Costa and Hutchings (2009) and Franzen et al. (2010). Retardation of material flow into the die has been observed in perpendicular orientation of texture to the drawing direction, hence yield a product with wave defect and in the meantime damaged the blank surface. Whilst parallel texture has no constraint effect on drawability of material flow. Besides that, they claimed that ratio of surface texture also significantly affected surface quality of aluminium product. Texture with small texture ratio of 0.3 triggered the formation of galling defect, but the defect was conspicuously reduced when increasing the ratio up to 0.5. Because of parallel texture improved the deformation of material, Zheng et al. (2015) adopted similar type of texture in hot stamping work. The parallel texture has encouraged reduction in temperature difference between top and side areas, thereby contributing to the more uniform deformation with no occurrence of necking defect.

In a subsequent investigation, Zheng et al. (2017) changed the straight groove texture on blankholder surface into radial groove texture and studied the effect of large texture ratio from 1 to 3. From the hot stamped final products as depicted in Figure 4, it was very conspicuous that aluminium alloy experienced severe flange wrinkling at texture ratio of 3 and 5. The occurrence of minimal wrinkle which has no significant effect on drawability of hot stamping process only observed in the texture ratio of 0 and 1. These results implied that unappropriated physical property of surface texture would lead deterioration in lubrication condition and deformation of metal and subsequently degraded the surface quality of final product.

Table 4: Application of surface texture in metal forming by various researchers.

Type of metal forming	Type of surface texture	Description of surface texture	Findings
Strip drawing (Costa and Hutchings, 2009)	Circle	w: 130 ± 10 (μm), h: 3.6 ± 0.3	Circular texture gave higher friction value than the smooth surface.
	Groove in parallel and perpendicular orientation	w: 30 ± 5 (μm), h: 3.0 ± 0.3	Textures oriented parallel to the drawing force increased friction coefficient and drawing force.
Deep drawing (Franzen et al., 2010)	Longitudinal groove	n: 19, d: 2 mm	Longitudinal/parallel triggered a formation of gouges, thus not recommended
	Transverse groove	n: 14, d: 3 mm	Transverse and zigzag pattern greatly capable in controlling material flow and reduced friction and surface roughness
	Zigzag pattern	n: 22, d: 2 mm	
Strip drawing (Sulaiman et al., 2017)	Groove oriented perpendicularly	d: 0.23 mm, 0.46 mm, 0.92 mm	Reduction in drawing load and friction were observed at d= 0.46 and 0.92 mm only.
Cold stamping (Zheng et al., 2015)	Perpendicular groove	Ratio (h/d): 0.3, 0.5, 1.0	Perpendicular texture constraints the material flow into die
	Parallel groove		Severe galling defects observed at ratio of 0.3. but reducing with texture ratio
Hot stamping (Zheng et al., 2015)	Parallel groove	Ratio (h/d): 0.3, 0.5, 1.0	Surface texture has reduced temperature loss, hence improved deformation of metal
Deep drawing (Zheng et al., 2017)	Radial groove	d: 1 mm, θ : 2.5° Ratio: 1, 3, 5	Radial texture deteriorated flow of material, hence induced wrinkling formation Formation of wrinkles worsen with increasing texture ratio
Hot stamping (Shihomatsu et al., 2016)	Spherical	w: 100-300 μm h: 30-150 μm d: 177-531 μm	Worst lubrication performance was observed in texture with the smallest, diameter, depth and spacing
Cold extrusion (Nurul and Syahrullail, 2016)	Spherical	w: 2.0 mm h: 0.03 mm d: 1.0 mm	Reduction in extrusion load and surface roughness
Deep drawing (Lin et al., 2015 and Lin and Yang, 2016)	Microridge	h: 0.019 mm	The texture improved friction property, drawability of metal, minimized stress, retarded the occurrence of defects and reduced production stage



Figure 3: Quality of stamped product at various texture ratios (Zheng et al., 2017).

In another hot stamping experiment, Shihomatsu et al. (2016) considered variant parameters of surface textures in order to study the effect of simultaneous mechanisms on the performance of metal forming. The varied parameters are diameter (100, 150, and 300 μm), depth (30 and 150 μm) and the distance between each texture (177, 266, 420, and 531 μm). Shihomatsu and his co-workers reported that texture with smallest diameter, depth and spacing exhibited the worst performance in terms of formation of wear, consequently provoked the occurrence of surface defect of galling. Whereas the best performance was obtained by the texture consists of maximum diameter of 300 μm , largest spacing of 531 μm and 150 μm in depth. Such texture enhanced the retention of lubricant and stiffness of the lubrication film, thus prevented metal-to-metal contact. The authors also emphasized that by optimizing the parameters of surface texture, the lifetime of dies could be lengthened. In very recent strip drawing experiment, Sulaiman et al. (2017) also concluded that friction and drawing load are hugely affected by the distance of each textures. The authors varied the distance of each textures at $x = 0.23, 0.46$ and 0.92 mm. The improvement in lubrication condition and reduction of drawing load were significantly observed at the texture distance greater than 0.46 mm. Distance of texture below than 0.46 mm led to a large drawing load than smooth surface. Similar behaviour was observed in a sheet metal forming where a large texture diameter size of 100 μm require highest punch force due to the lowest transfer rate of lubricants between surface textures. Besides that, there was a time delay for the lubricant to fill up the large surface texture compared with 10 μm and 50 μm diameter size for the same volume of lubricant flowed at the interface. At the time lubricant already filled the small diameter of surface texture, a large texture was still filled with lubricant and air bubbles (Shimizu et al., 2019).

Friction condition in micro-sized system is more critical than the macro-sized due to the influence of "size effect" (Wang et al., 2015). In order to provide good lubrication condition at narrow tool-workpiece interface, Lin et al. (2015) adopted the application of texture (micro-ridge) on punch surface in the forming process of micro-sized cylindrical cup. From the experimental and numerical studies, micro-ridge has been successfully reduced the frictional force and drawing load, consequently enhanced drawability of copper alloy by at least 100% as elucidate in Figure 4. The authors emphasized that by applying micro-texture in the forming system, stress near the punch nose has been minimized and thus retarded the occurrence of surface defects like wrinkle, crack or necking. In the extended experiment, Lin and Yang (2016) revealed that by

introducing microridge punch in multistage deep drawing process, the original eight-stage forming processes have been reduced to six-stages only. The results demonstrated that the application of surface texture not only enhanced tribological and deformation performances but also effectively utilised the production process, thereby contributing to the reduction in manufacturing cost and time.

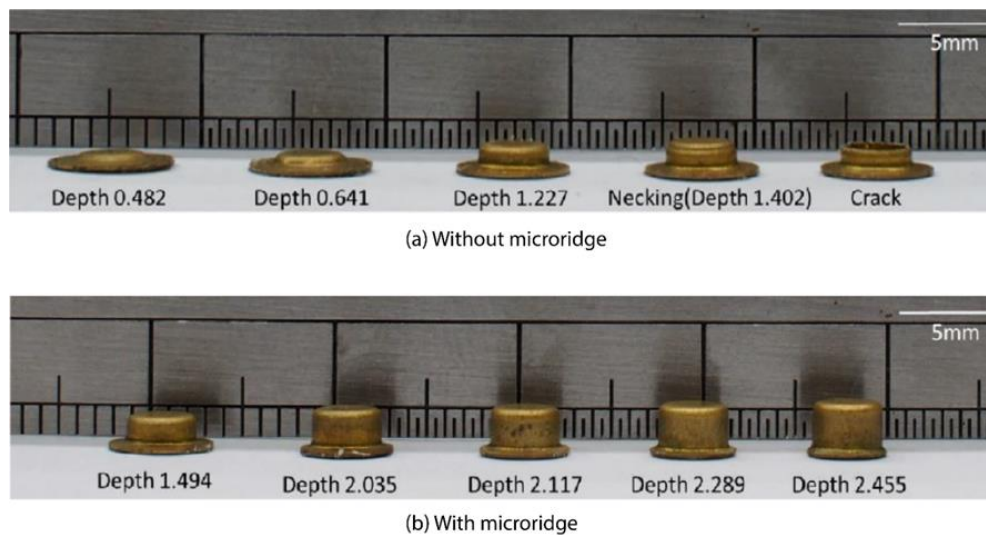


Figure 4: Formability of cylindrical cups for punch with/without microridge (Lin et al., 2015).

A detail of the application of vegetable oils in metal forming process is presented in Table 5. The main objective of research done by Lovell et al. (2006) was to investigate a potential of environmental friendly lubricant for sheet metal stamping work. The authors studied the performance of natural canola oil and canola oil blended with boric acid, then compared with unlubricated condition and commercial transmission fluid. From the experimental results, transmission fluid exhibited the superior performance as the fluid gave the lowest friction ($\mu = 0.41$) and surface roughness ($R_a = 0.65 \mu\text{m}$) values while unlubricated condition demonstrated the worse results ($\mu = 0.5$, $R_a = 0.70 \mu\text{m}$). The used of canola oil resulted in moderate performance of friction and surface roughness ($\mu=0.43$, $R_a = 0.67 \mu\text{m}$), in which slightly improved the performance of unlubricated case. However, when natural canola oil was chemically modified with the addition of solid boric acid particles, tribological properties of canola oil was significantly enhanced and became superior to transmission fluid. Both friction and surface roughness values of the new canola oil-boric acid formulation have been substantially reduced to 0.23 and $0.58 \mu\text{m}$, respectively.

Similarly, Syahrullail et al. (2011) suggested that palm oil-based lubricant performed better than mineral oil-based lubricant in cold extrusion process. The authors applied three types of lubricants on the taper die surface, which are refined, bleached, deodorized (RBD) palm stearin oil, additive-free paraffinic mineral oil (PMO) of VG95 and VG460. As depicted in Figure 5, the used of RBD palm stearin oil led to the huge reduction in the extrusion load and surface roughness value in comparison with both mineral oils. Zareh-Desari and Davoodi (2017) utilized the application of nanoparticles in vegetable oils. They inferred that by adding copper oxide and silica nanoparticles with the optimum percentage into rapeseed oil or soybean oil, maximum

enhancement in friction reduction could be obtained in the range of 21% to 31%. In addition, depletion in the forming load in the range of 2.3% to 5.32% has been observed in the mixture of vegetable oils and nanoparticles. In a recent study, Oliveira et al. 2020 reported that applying sunflower oil, corn oil or canola oil between aluminium billet and die surfaces resulted in a reduction of surface roughness of after cold extrusion process and a maximum reduction was observed in canola oil. While, the present of soybean oil increased the roughness of aluminium billet which behaved similarly to a commercial mineral oil. Furthermore, soybean oil required the highest extrusion load and the lowest load force demonstrated by corn oil.

Table 5: Summary of research on the application of vegetable oils in metal forming process

Type of metal forming	Type of vegetable oil	Physical properties	Friction of coefficient, μ	Surface roughness R_a (μm)	Results
Stamping (Lovell et al., (2006)	Canola oil		0.43	0.67	Enhanced the lubrication condition but cannot surpassed the performance of transmission fluid. The oil became superior when blending with boric acid.
	Canola oil with boric acid	-	0.23	0.58	
Cold extrusion (Syahrullail et al., 2011)	RBD palm stearin	VI: 159 Iodine value: 56-59.1	-	0.42	The palm oil-based lubricant provided the lowest extrusion load and surface roughness than that of mineral oil-based lubricant
Cold extrusion (Ajiboye et al., 2014)	Palm oil, Coconut oil, Groundnut oil, Olive oil	At 40 ⁰ C, the highest viscosity value demonstrated by palm oil and olive oil gave the lowest value	-	-	Palm oil gave the lowest extrusion load, while the highest value obtained from groundnut oil. Palm oil also improved ductility, strength and hardness of the alloy.
Cold extrusion (Nurul and Syahrullail, 2017)	RBD palm kernel	Relative density: 0.86 VI: 176 Kinematic viscosity at 40 ⁰ C: 31.32	-	0.218	The performance of palm oil in extrusion load and surface roughness was comparable with commercial oil.

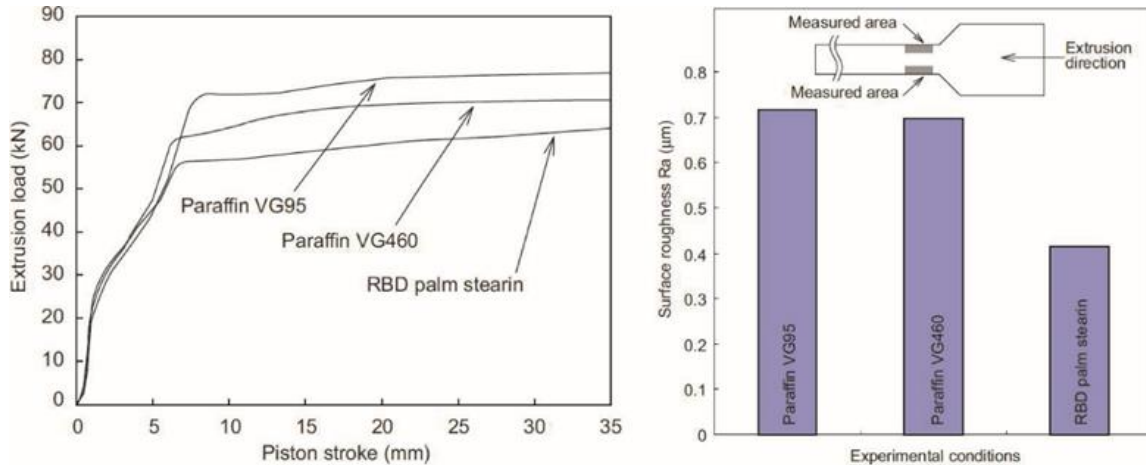


Figure 5: Load and surface roughness of different lubricants (Syahrullail et al., 2011).

In another study, Ajiboye et al. (2014) analysed the effectiveness of various vegetable oils such as palm, coconut, groundnut and olive oils as a potential forming lubricant oil. From the extrusion tests, the authors reported that the minimum extrusion load required to extrude aluminium 6063 billet was obtained when applying palm oil at die-billet interface, followed by olive, coconut and groundnut oils. Because of the amount of extrusion load is significantly governed by lubrication condition at die-billet interface, it can be concluded that lowest value of friction coefficient was provided by palm oil, whilst groundnut oil gave the highest value. Besides that, palm oil also encouraged the maximum improvement in mechanical properties of the billets in term of highest yield strength, ultimate tensile strength and ductility. Nurul and Syahrullail (2016) took into consideration both applications of surface texture and vegetable oil in cold extrusion process of aluminium. Both researchers employed spherical texture with diameter of 2.0 mm, 0.03 mm depth and spacing of 1.0 mm as presented in Figure 6. While the tested lubricants were RBD palm stearin, PMO VG95 and PMO VG460. They observed that without surface textures, the used of palm stearin not showing any betterment as extrusion load required during forming process was substantially larger than PMO VG95. But the extrusion load was enormously reduced and gave the least value once the smooth taper die changed to the textured surface. Apart from that, RBD palm stearin also exhibited the smallest values of *surface roughness* for with and without surface textures compared to the both mineral oils. In their extended study, Nurul and Syahrullail (2017) used another type of palm oil-based of RBD palm kernel. They found that the performance of RBD palm kernel in term of reduction of load and surface roughness was quite similar with RBD palm stearin and slightly better than mineral oils. From the metal flow of extruded aluminium billet as depicted in Figure 7, deformation of metal when using RBD palm kernel was comparable with mineral oils. In the metal forming process, the forming load, heat generation, flow of metal and surface quality of the final product are governed by tribological conditions at the tool-workpiece interface.

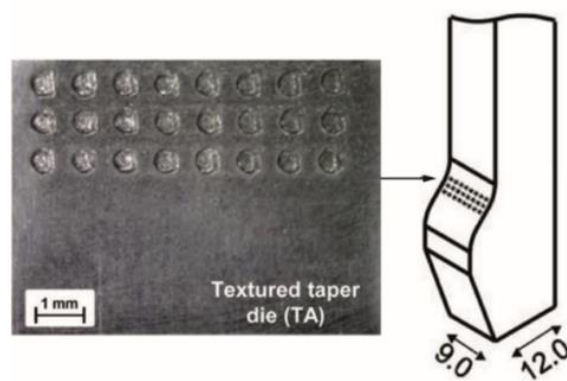


Figure 6: Textured taper die with spherical shape for cold extrusion process (Nurul and Syahrullail, 2016).

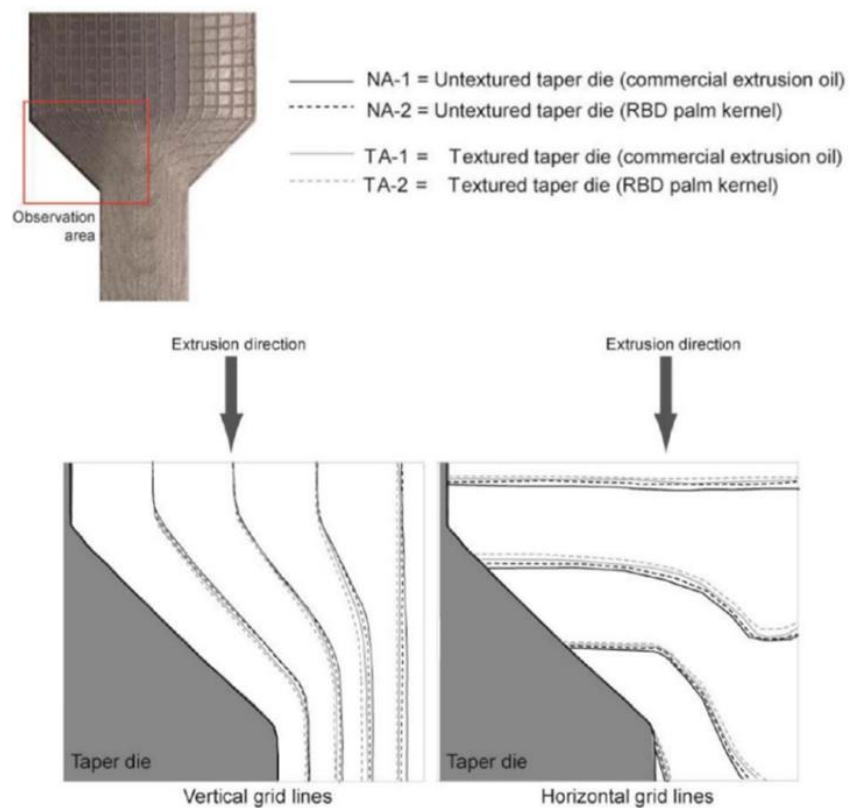


Figure 7 Metal flow of billet with different surface and lubricant conditions (Nurul and Syahrullail, 2017).

5.0 CONCLUSIONS

The critical state of the environment and finite resources of mineral oil have urged metal forming industries to find a clean forming process. Thus, this review focussed on the application

of vegetable oils and surface texture, which show potential as sustainable and environmentally friendly approaches for implementing a cleaner process. Current research on the application of vegetable oil in metal forming is limited to natural oil. The performance of natural oil is better than dry lubricant, but it is still not superior to mineral oil-based forming lubricant. To find an application in the metal forming industry, current research must shift to the blending of chemically modified vegetable oil with additives. In fact, commercial forming lubricant contains various additives that make it useful in a metal forming environment. Any new formulations of vegetable oil must pass biodegradability, sludge, toxicity and eco-toxicity testing before they can replace mineral oil-based lubricant as the industry standard. Major challenges in the formulation of vegetable oil-based lubricants are synergy between the modified vegetable oil role as a base oil and the current use of additives, compatibility with the current mechanical system, continuous supply of the feedstock and high production cost.

The main purpose of engraving the tool's surface with texture is to trap lubricant, thereby improving the lubrication condition of the smooth surface. However, the occurrence of surface defects as a result of deterioration of the lubrication film and material flow indicates that the physical characteristics of surface texture may be more critical than trapping lubricant. Thus, optimising the physical dimensions of the texture should be considered as an area for further research. This should investigate the optimum size, depth, orientation, distribution and total number of textures. A simulation study could help researchers to find the optimum dimensions by developing a theoretical model, so that fabrication costs and implementation time in metal forming systems can be minimised.

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