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Minimum quantity lubrication in cold work drawing process: Effects on forming load and surface roughness

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Abstract

In this study, experimental analysis has been employed to evaluate the effects of minimum quantity lubrication on the deformation of aluminium workpiece over a tool. The effects of lubricant on forming loads and surface finish were evaluated under dry and lubricated conditions between die-workpiece sliding surfaces. Palm olein (PO) with dynamic viscosity of 38.9 mPa.s at 40 °C in 1, 5, 10, and 20 mg amounts were used as test lubricant. A constant forming speed of 10 mm/s on the workpiece was used as inputs for the experimental analysis. The load-displacement behaviour was observed during the steady-state condition. It was shown that significant differences exist between lubricant quantity, load-displacement distribution and surface finish of the product.

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Keywords: Tribology; metal forming; minimum quantity lubrication; forming load; surface roughness.

1. Introduction

Metal forming plays a significant role in manufacturing industries. Friction problems are important because they can cause a poor quality of surface finish product and can introduce delays in the process of metal forming. Many studies [1-3] on the friction coefficient have been performed by comparing friction characteristics between experimental and FE results. The forming load increases as the material flowed through the die opening, but it depends on the contact pressure occurred on the die sliding angle in the deformation zone. The higher the die angle, the more forming load is needed in order to force the material to flow through the die opening with the friction moving against the material flow along the die-workpiece contact surface.

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Wear generated by the presence of friction on die-workpiece contact surface can cause debris to form, which may affect the quality surface roughness of sheet metal forming and forming load. Workpiece and tool dies are characterized by surface roughness. It was found that the roughness on the contact surface has an influence on friction during metal forming processes [4]. Nowadays, metal forming lubricant evaluation is very demanding because of stringent surface requirements in the finish product [5]. Lubricants are evaluated to ensure their lubricity as well as to ensure that the desired film thickness is achieved. Syahrullail et al [6] evaluated lubricity of palm oil in cold work forward plain strain extrusion. The authors found that palm oil has better lubrication properties than paraffinic mineral oil.

In analyzing metal forming processes, knowledge of friction is important, especially when the microstructure evolution and criteria for limiting phenomena are predicted through numerical simulation. At present, Coulomb's friction model and von Mises friction model are widely used [7] in analysis of the metal forming process. Therefore in this study friction coefficients will be determined by FE analysis focusing on cold work drawing process. However, the drawing process is somewhat similar to extrusion, which is a workpiece characterized by compressive forming; except that in drawing, the workpiece undergoes combined tensile and compressive forming. The drawing process involves an operation in which the cross-sectional area of a workpiece is reduced or changed in shape by pulling it through a converging die. Meanwhile extrusion is a process done by pressing the workpiece through the converging die.

As the development of processes and tooling is very important in deciding forming loads and metal flow, the occurrence of failures should be controlled in order to minimize defects and wear of the tool and the product as well as to control the accuracy of necessary output results predicted. Due to growing environmental and manufacturing defect concerns, palm olein will be used as a test lubricant in the cold work drawing process. In order to obtain a low friction coefficient, a limited amount of lubricant between the die-workpiece contact surfaces is necessary. Therefore, the effect of lubricant quantities on load-displacement distribution during the steady-state condition and surface roughness of the product surface finish were evaluated, and the limit of lubricant quantity was determined to decrease the waste of oil.

2. Research Methodology

2.1. Test Materials

The principal experimental material was commercial pure aluminium A1100. The tool die used in the experiment was hot work hardened tool steel SKD11. The palm olein with dynamic viscosity of 38.9 mPa.s at 40 °C was studied (see Table 1). Palm olein properties were described in details in Table 1 [8]. The necessary parameters for elastic plastic analysis such as mass density ρ, elastic modulus E, and Poisson's ratio v, are shown in Table 2. In experimental analysis, materials are important inputs. Therefore, pure aluminium A1100 was tested with a unidirectional testing machine which was designed based on standard test method ASTM E8-91. Typical results obtained from the uniaxial tensile test of the longitudinal orthogonal direction are shown in Fig. 1. The nonlinear stress-strain behaviour of aluminium A1100 graph was then converted from the engineering stress and strain measures into true stress σ_{true} and true strain ε_{true}, as shown in Fig. 1. The material behaviour in Fig. 1 follows similar observations of the same material tested in Ref. [9].

Table 1. Lubricant properties of palm olein [12].

Properties	Value
Specific density 25 ^{o}C	0.873
Dynamic viscosity at 40 ^{o}C (mPa.s)	38.9
Dynamic viscosity at 100 ^{o}C (mPa.s)	5.3

Table 2. Material properties of aluminium A1100 and SKD11.

Properties	A1100	SKD11
Density ρ (kg/m^3)	2700	8030
Young's modulus E (GPa)	69.97	210
Poisson's ratio v	0.33	0.3

2.2. Cold Work Drawing Experiment

The present investigation was based on previous experimental procedures [10, 11] for the evaluation of palm olein as a test lubricant in the cold work drawing process. Some of the basic parameters in the experimental apparatus are shown schematically in Fig. 2. An aluminium A1100 workpiece was drawn through a 45^o and 9^o taper die exit angle at room temperature. The cold work drawn rig was designed in accordance to the appropriate criteria for the evaluation of load-displacement behaviour for cold work drawing process. The principal material of aluminium A1100 workpiece with 5 mm thick t sheet with tolerance 0.05 mm was shaped using NC wire cut electric discharge machining device. The workpiece were heated for 3 hours at 350 °C to adjust the chemical composition of the workpiece, annihilate rolling texture and establish recrystallised structure with isotropic mechanical properties. The preparation of die used the same method as well. The die was hardened for 10 hours at 950 °C and then, quenched into water to improve wear resistance and reduce friction.

For each specimen in the experiment, the surface of taper dies that was in contact with the workpiece was cleaned and polished with abrasive paper and acetone to ensure all components were clean and in good condition. The outer wall, container, dies, and workpiece were cleaned with acetone to remove oil, grease, and other surface contaminants. The lubricant quantity in an amount of 1 mg was spread over the die plane. The die was weighed using micro weight scale before and after being lubricated. The lubricated dies were carefully and symmetrically positioned in the die holder. The hydraulic press machine moved the workpiece downward to produce finish product. Load cell recorded forming load as a function of displacement in time behaviour and displayed the load data in computer software. The load readings were recorded for every 0.01 s downward movement of the end tip of workpiece. Finally, once the workpiece movement was stopped at 20 mm downward, the dies were disassembled and the split dies were opened to remove the drawn product. The load-displacement graph was plotted for lubricant quantity of 1 mg. The whole procedure was repeated for lubricant quantities of 5, 10 and 20 mg and finally for a dry condition on the die-workpiece contact surfaces.

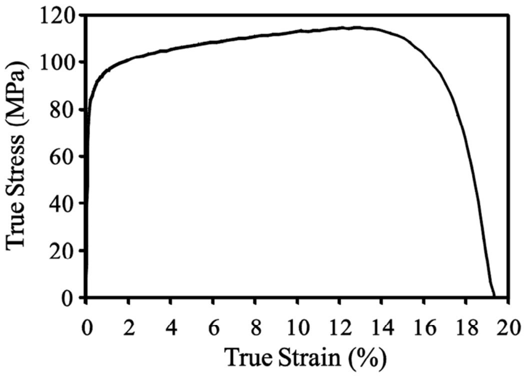


Fig. 1. Material characteristics of aluminium A1100.

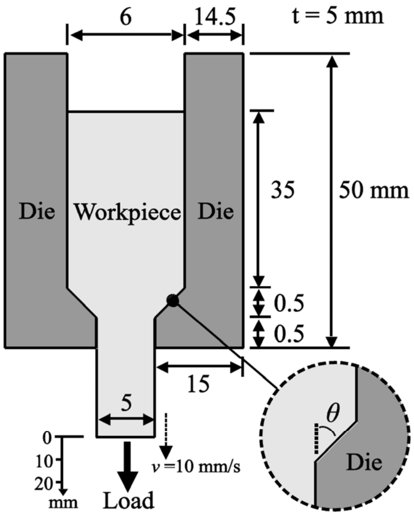


Fig. 2. Schematic diagram of cold work drawing (all dimensions in mm).

3. Results and Discussion

In this study, the mechanics of cold work drawing operation began by placing the workpiece in the die container at the die opening reduction region. The forming load was applied to the end of the workpiece. This forming load was increased until it reached a peak value that coincided with the peak radial normal pressure in the die wall. At this instance, the drawing began to extrude the product through the die opening. In this analysis, steady-state condition was considered; this refers to the condition in which there was no more increment of forming load. This occurred when a volume of plastically deformed zone had emerged from the die until the end of the drawing.

The main factor influence the evaluation of friction coefficient μ for the dry and lubricated die-workpiece contact surfaces was the value of die angle θ which maximized the forming load [10]. It is important to optimize the friction coefficient to control residual stress and the shape precision of the product. In this analysis, three zones of deformation were identified; zone I was the undeformed region, zone II was the plastically deformed in a zone that has θ of 45° and 9° taper die reduction, and zone III was the final deformed (product) region. In order to consider the high performance involved in cold working drawing operation, a lubricant has to be selected which will not shear too easily and allow rupture and failure, a situation most probable with high viscosity lubricants. In this study, palm olein has been adopted for the cold work drawing experiment because it has a better lubrication performance than paraffinic mineral oil [11].

Fig. 3 shows the experimental result of cold work drawing with the dry and lubricated conditions on the die-workpiece contact sliding surfaces for the die angle θ of 45^{o}. The lubricated conditions were measured based on lubricant quantity in an amount of 1, 5, 10, and 20 mg. Among the four investigated, palm olein with the lubricant quantity of 5 mg gave the best performance during steady-state condition. On the lubricated contact surface, the values of 1, 10 and 20 mg were quite close to that of lubricant quantity of 5 mg. For all forming loads, a dry contact surface gave the highest value. Based on graphically determined die angle as shown in Fig. 4, the maximum forming load obtained in the steady-state condition for the cold work drawing operation decreased with reduction in tool die angle. In other words, the figure shows that the increase in forming load resulted from an increase in coefficient of friction. The decrease can further be explained by assuming that as the forming load increases the lubricant quantity decreases; a small amount of lubricant exhibits a greater resistance to shear and the frictional force at zone II in the deformation region.

It is worth mentioning that coefficient of friction depends of amount of lubricant and a constant forming load during steady-state condition can mean that the forming load on the die wall is increased as the workpiece sliding length is reduced. Fig. 3 and Fig. 4 shows that low friction coefficient reduced the forming load. Poor lubrication caused by the inappropriate lubricant quantity between the die and the workpiece increased the forming load and reduced the shape precision of the product. Due to the poor lubrication on the die-workpiece contact sliding surfaces also may initiate galling caused a great damage to the surface quality of the product. Therefore, it is very important to design the proper surface texture of the product based on lubricant quantity because metal forming processes are the method not only to manufacture products but also to manufacture materials [13]. Fig. 4 also shows that the die geometry and die-to-die opening ratio may contribute to these results as well [2, 10]. These conditions can be explained by the increasing radial normal force that particularly occurred at the taper die region.

The average value of the arithmetic mean surface roughness Ra of the product surface finish was measured and shown in Fig. 5. The measured product surface finish is the surface that in contact with the tool die and the container. The direction of surface roughness measurement is perpendicular to the drawing direction. From Fig. 6, comparison among the tool die angles shows that the surface roughness Ra of the product surface finish drawn by using palm olein have different forming load values. It was observed that the drawn product with a dry contact surface gave higher surface roughness Ra and coarser surface finish compared to lubricated contact surface (see Fig. 7). This phenomenon can be explained by the occurrence of a thick layer of lubricant produced between die-workpiece contact surfaces and the asperities on the workpiece surface are not further to be flattened by the tool surface. Hence, the boundary lubrication condition would not occur, which allowed the workpiece to deform similarly to the tool surface quality [6].

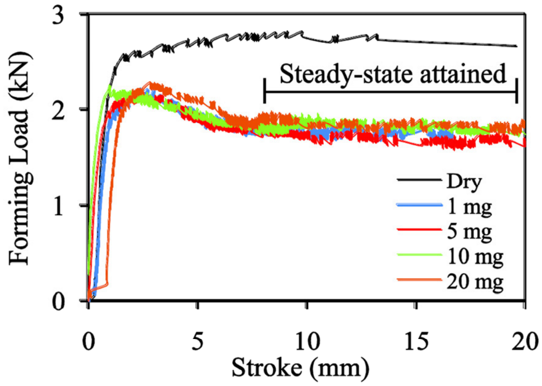


Fig. 3. Experimental result of cold work drawing with die angle θ of 45° for the dry and lubricated conditions in an amount of 1, 5, 10, and 20 mg.

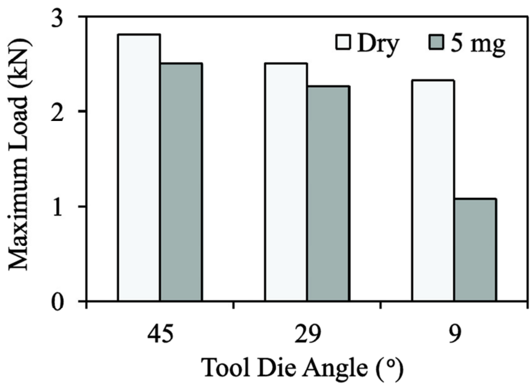


Fig. 4. Experimental result of cold work drawing with die angle θ for the dry and lubricated condition in an amount of 5 mg.

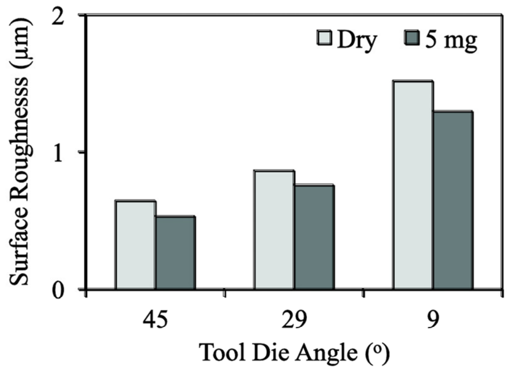


Fig. 5. Experimental result of cold work drawing with tool die angles θ the dry and lubricated conditions in an amount of 5 mg.

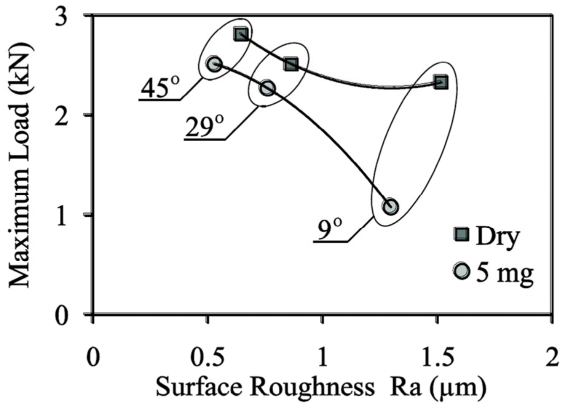
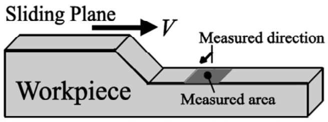


Fig. 6. Relationship between maximum load and surface roughness for different tool die angles θ

Fig. 7 shows the surface finish of the product captured by optical microscope at three different areas; (A) undeformed region, (B) final deformed region just right after die opening, and (C) surface finish of the final deformed region. It was observed that friction conditions under dry contact sliding surface resulted in high forming load, high friction and high contact pressure in the deformation region are very severe. In addition, the dry contact surface has a great influence on the friction behavior when the workpiece under plastic deformation during the cold work drawing process. Furthermore, the uneven surface finish was generated due to the surface expansion grain slip. This means that metal forming process cannot perform satisfactorily under dry friction because the plastic deformation is the most severe near the taper die edge surface of the billet where peak stress occurred where the lubricant is needed to overcome the friction on the die-workpiece sliding surface.



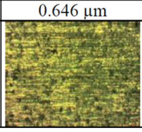
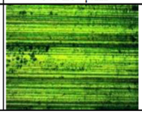
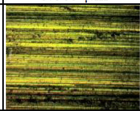
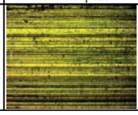
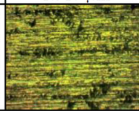
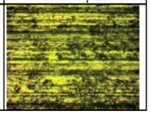
Tool Die Angle	45 °		29 °		9 °	
Lubricant Quantity	Dry	5 mg	Dry	5 mg	Dry	5 mg
Maximum Forming Load	2.81 kN	2.51 kN	2.51 kN	2.27 kN	2.33 kN	1.08 kN
Coefficient of Friction μ						
Surface Roughness Ra	0.646 µm	0.529 µm	0.865 µm	0.760 µm	1.517 µm	1.297 µm
Optical Microscope Image						

Fig. 7. Comparisons of friction coefficient, optimal microscope image and surface roughness Ra of the product surface finish.

4. Conclusion

The effects of minimum quantity lubrication during the cold work metal forming process on load-displacement and surface finish of the product were examined and compared. The forming loads were evaluated based on a constant forming speed of 10 mm/s on the end tip of the workpiece. The minimum lubricant quantity is 5 mg for the cold work metal forming process, so that the lubrication condition lies within the elastohydrodynamic lubrication regime. Hence, this study supports the experimental findings that the forming load increases with surface roughness and coefficient of friction and a coarser surface finish of the product. The comparison concludes that by increasing the coefficient of friction, the forming load and the contact pressure generally increase for each lubricant amount increase. In addition, it is very important to design a proper surface texture of the product based on lubricant quantity. The load-displacement obtained in the cold work drawing operation decreased with reduction in die angle. Finally, this paper demonstrates that with the selection of the right amount of palm olein as the metal forming lubricant, friction on the die-workpiece contact surface in cold work drawing process can be reduced. It may be concluded that a minimum lubricant quantity in the metal forming process is required to lighten the tribological load as much as possible.

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