ISSN 2229-5518

The Use Of Superplastic Tin-Lead Alloy as a Solid Lubricant in Metal Forming Processes in General and in Forging in Particular

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Abstract— The main function of a lubricant in any forming process is to reduce friction between the work piece and the die set, hence reducing the force and energy requirement for forming process and to achieve homogenous deformation. The free upsetting test is an important open forging test. In this paper, superplastic tin-lead alloy is used as solid lubricant in the free upsetting test of ferrous and non-ferrous materials and compared with eight different lubricants using the following three criteria: one comparing the value of the reduction in height percentages, i.e. the engineering strain, in identical specimens of the same material under the effect of the same compressive force. The second is comparing the amount of barreling produced in each of the identical specimens, at each lubricant. The third criterion is using the specific energy, i.e. the energy per unit volume consumed in forming each material, using the different lubricants to produce the same reduction in height percentage of identical specimens from each of the two materials, namely: die steel, D2, and stainless steel. It was found that the superplastic tin-lead alloy lubricant has produced higher values of reductions in height percentage and less barreling in the two ferrous materials, used in this work, among the different used lubricants.

Index Terms— Different lubricants, Free upsetting, Solid lubricants, Superplastic tin-lead alloy

1 Introduction

In metal forming processes, friction at the punch and die/work piece interface plays a significant role on the load and energy requirements, tool life, and the quality of the finished product, [Bakhshi, 2002]. The role of lubricants is to reduce friction between the die set and the workpiece and to reduce heat-transfer from the billet to the die during the high strain rate forming processe, which are normally accompanied by heat generation, hence it reduces the force and energy required for the forming process. The major factors affecting friction include : the normal stress along the punch or die workpiece material interface, the lubrication condition, the relative velocity, the working temperature, the surface roughness, and the mechanical properties of the punch and die materials, [Joun et. al, 2009; Jeong, 2001]. In addition, lubricants are necessary to prevent adhesion, scratching, galling and material transfer, [Rao et. al., 2001].The selection of lubricant for a forming process in general depends on two main parameters:

1. The characteristics of the metal of the work piece which include: yield strength, rate of work hardening, coefficient of friction between the work piece material and the punch and the die sets, rate of chemical reaction between the work piece material and the lubricant and the tendency to a form a surface film.

2. The manufacturing process and the severity of the process, e.g. lubricants which are considered effective in one manufacturing process may be very ineffective in other manufacturing process. Similarly, the working conditions, for example lubricants which may be effective in cold working may be very ineffective if used in hot working of the same process, e.g.; graphite suspended in alcohol may be very effective in cold forging of steel below 500oC whereas they are very ineffective when used in hot forging of steel. According to different physical contact conditions, lubricants can be divided into three types: solid (as lead), semi-solid (as grease) and liquid lubricants (as oils). In this paper, only the solid type will be dealt with. Solid lubricants are solid materials, which reduce coefficient of friction and wear of rubbing parts preventing direct contact between their surfaces even under high loads. They may be present in the friction area in forms of either dispersed particles or surface film. The main requirements of solid lubricants include: low shear strength in the sliding direction. This property provides low coefficient of friction due to easy shear movement of the lubricant material, High compression strength in the direction of the load (perpendicular to the sliding direction). A solid lubricant possessing high compression strength is capable to withstand high loads without sufficient direct contact between the rubbing surfaces, and good adhesion of the solid lubricant to the substrate surface. This property provides a presence of the solid lubricant on the part surface even at high shear stresses. The best combination of the first two properties exists in materials like graphite, molybdenum disulphide or boron nitride which have lamellar crystal structure. Solid lubricants have the following advantageous: ability to work under high loads, High thermal stability and diversity of the application forms. Beside these advantages, solid lubricants have the following disadvantage: higher coefficient of friction and wear as compared to hydrodynamic region, low stability of the lubrication film and less convenient system of the lubricant delivery to the friction surfaces. In contrast to solid lubricants, fluid lubricants are continuously supplied, filtered and cooled. The literature on solid lubricants is voluminous which includes their classifications

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ISSN 2229-5518

and applications [Mendez, 2008; Saiki et al, 2006; Caminage et. al., 2007; Arentoft et. al., 2009; Mulhll et. al., 2003; Kunogi, 1954; Hawkyard, 1967; Male, 1962; Male et al., 1964; Saiki et al, 2003; Al-Huniti and Zaid, 2004; Shen, 2001; Wang, 2007; Zaid, 2004; Zaid and Al-tamimi, 2011; Zaid and Al-tamimi, 2014] .Only some of these references which are very relevant to the work in this paper.[Kunogi, 1962], has investigated experimentally the deformation of hollow cylinders under axial loads, whereas [Hawkyard and Johnson, 1967] have reported an analysis of the change of geometry of a short hollow cylinder during axial compression. [Male,1962; Male and Cockcroft, 1964] developed a method based on the enlargement and contraction of the hole in a ring under quasi-static compression for determining the coefficient of friction of metals under conditions of bulk deformation. [Saiki and Marumo, 2003; Saiki et al, 2006] have investigated the effect of the surface roughness of the cutting tool using a detailed finite element method (FEM). They found that it influences the coefficient of friction, the local surface enlargement at the friction surface of material and solid lubricant thinning at the edge of tool–material interface. The change in the contact condition and the lubricant behavior were evaluated by continuously measuring the ultrasonic reflection intensity from the contact interface between the tool and workpiece. The relationships between ultrasonic reflection intensity, forging temperature, lubrication, forging pressure and workpiece surface during forging were examined by [Saiki, et al, 2006] .[Al- Huniti and Zaid, 2004] studied the simulation of the upsetting ring using finite element analysis, FEA. [Wang, et al. 2007] analyzed the formation mechanism of surface friction in an extrusion process, where the relationship between friction coefficient and geometrical parameters of rough surface based on adhesive theory, was established. The deformation of fine-grained metallic materials, e.g. superplastic tin-lead alloy, their well-established industrial applications particularly in the automobile industry and their recent developments were presented and discussed by [Zaid, 2004]. Recently, [Zaid and Al-Tamimi, 2014], investigated experimentally the cavity closure in the free upsetting tests using open and semi closed dies using superplastic tin-lead alloy at room temperature and low strain rate to simulate the behavior of steels at high temperature and high values of strain rate. They succeeded in the use of semi-closed die to have complete closure of the cavity at high reduction in height. Superplasticity is a feature which allows the material to deform to large strains at low stress, much less than its yield stress if the material is deformed under certain conditions of temperature, strain rate and small grain size <10 μm, [Zaid, 2004]. As mentioned before, one of the main requirements of a solid is to have low shear strength. It is, therefore, anticipated that superplastic material may be a good solid lubricant. This formed the main objective of the research work reported in this paper.

2 MATERIALS, EQUIPMENT AND EXPERIMENTAL PROCEDURES

2.1 Materials

D Specimens. The specimens used for the free upsetting tests throughout this research work were manufactured from two different materials, namely: die steel, D2, and stainless steel. These were supplied in the form of cylindrical rods, from local suppliers.

Lubricants. Eight different lubricants were used for lubrication in the free upsetting tests, namely: olive oil, quartz 2500 SAE 40 mono grade oil, quartz 5000 SL 20W50 multi grade oil, transmission 80W90 oil, paraffin wax, teflon, molybdenum disulfide (MoS2) grease and superplastic tin- lead alloy. The characteristics of these lubricants are shown in Appendix A. The tin-31.9 lead alloy which was used as solid lubricant was prepared from high purity tin and lead granules.

2.2 Equipment

An electric furnace of 1200oC was used for melting the tin and lead granules, graphite crucible was used for this purpose, and graphite rod was used for stirring. The tin-31.9% lead melt was poured in thick brass cylindrical rods of the dimensions shown in Table 1.

TABLE 1
DIMENSIONS OF THE BRASS CYLINDRICAL RODS

Rod number	External Diameter (mm)	Internal Diameter (mm)	Height (mm)
1	50	14	130
2	60	15	80
3	50	8	80

2.3 Experimental Procedure

The experimental work was started by producing the tin-38.1% lead eutectic alloy in the form of cylindrical rods, and then machined in accordance with the inner dimension of extrusion die. The machined rod is then extruded in the extrusion die shown in Fig.1 to increase the degree of its super plasticity.

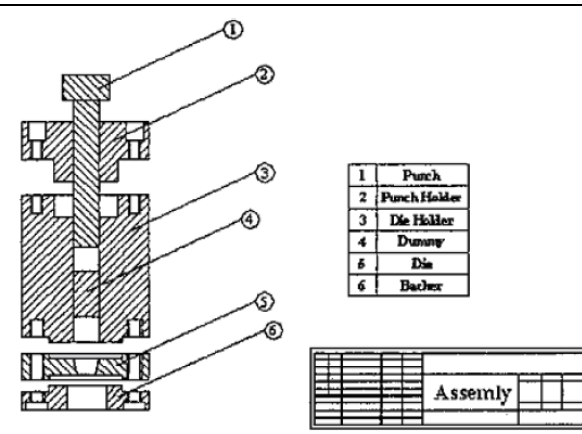

Fig. 1. Extrusion Die Assembly

The extruded rod was kept in ice in a flask to avoid grain growth of its structure. It was kept in the flask until it was cut into discs of 14 mm diameter and 3 mm thickness. These discs were compressed between the flat plates of the universal testing machine of 1000 KN capacity to a thickness of 0.3 mm, prior to their use as solid lubricant at the upper and lower surfaces of the test specimens of the different metals in the free upsetting tests using the same universal testing machine. Free upsetting tests were carried out on specimens, from each material, having an aspect ratio h/d =1 applying the different lubricants using the same universal testing machine at the same cross head speed of 0.5 mm/min and compressed to 40-50% of their original height. The load-deflection curve, autographic record, was obtained for each specimen under a specified lubricant from the eight different lubricants and the dry condition used throughout this work.

The final height and diameter of each specimen were measured using a digital micrometer to an accuracy of 0.001 mm. Finally, the specimens were sectioned across their diameters along their heights and traced using the contracer at a magnification of X5, to allow comparison of the amount of barreling under the effect of each lubricant on D2 and stainless steel specimens.

3 RESULTS AND DISCUSSION

In this paper, the following criteria were used to assess the performance of the different lubricants used including the superplastic tin-lead eutectic, when applied to two ferrous materials: die steel, D2 and stainless steel in the free upsetting test:

1. Based on the force required to produce the same reduction in height in a workpiece of the same dimensions and the same material, under the effect of the different lubricants where the effective lubricant will consume less force to produce the same reduction in height or vice versa the more effective lubricant will produce more reduction in height in specimens of the same material and dimensions.
2. Based on the energy required to produce the same reduction in height in identical specimens of the same material. The more effective lubricant will consume less energy in producing the same deformation, as the total work, wT, is consumed in the ideal deformation (plastic work), wP, work due to friction, wF, and the redundant work, wR, i.e. wT= wP + wF +wR. The first and the latter works are the same for the same forming process under the same conditions of temperature and strain rate. Hence, the difference will be due to the lubrication effectiveness, i.e. reduction of friction.
3. Based on the amount of barreling in the free upsetting test. The more effective lubricant will produce less barreling effect in identical specimens under the same deformation.

The results obtained throughout this work will be discussed based on these criteria for evaluating the effectiveness of the different lubricants used for the two materials, D2 and stainless steel in sequence.

3.1 Evaluation of Different Lubricants Based on the Force Required for Producing the Same Amount of Deflection in Die steel, D2, and stainless steel

Table 2 shows the results obtained for the different lubricants used with die steel, D2. It can be seen from the results of Table 2 that for die steel, D2, the superplastic tin- lead alloy, referred to as, S.P, there after is the most effective lubricant among the different used lubricants, reflected by the minimum final height, i.e. the maximum deflection, being 5.59 mm produced under the effect of 290 KN for the two specimens of S.P, to ensue repeatability, as compared to 310-317 KN for the other different lubricants i.e. reducing the force by a minimum of 7.4% and a maximum of 9.1%. The arrangement of these lubricants, regarding the required force on die steel, D2, specimens, is shown in the histogram of Fig.2.

TABLE 2
SUMMERY OF THE RESULTS OBTAINED FOR DIE STEEL, D2

sample #	Lubricant	original diameter (mm)	original Area Ao (mm2)	original height (mm)	Volume V (mm3)	Force (KN)	Force/Area (MPa)	final Height (mm)	Deflection (mm)	Final diameter (mm)	Total Work (N.mm)	Total Work/Volume WT/V (MPa)
1	dry condition	15.177	180.933	15.153	2741.74	315.547	1744	9.092	6.061	20.957	1215	443
2	dry condition	15.153	180.361	14.867	2681.37	315.906	1752	8.92	5.947	21.15	1192.5	445
	drycondition (Avg)	15.165	180.647	15.01	2711.55	315.727	1748	9.006	6.004	21.0535	1203.75	444
1	olive oil	15.143	180.123	15.077	2715.65	313.188	1739	9.046	6.031	20.753	1181.25	435
2	olive oil	15.173	180.838	14.793	2675.2	311.657	1723	8.876	5.917	20.857	1137.5	425
	oliveoil (Avg)	15.158	180.481	14.935	2695.43	312.423	1731	8.961	5.974	20.805	1159.38	430
1	SAE 40	15.157	180.457	15.233	2748.96	316.578	1754	9.14	6.093	20.927	1212.5	441
2	SAE 40	15.19	181.243	15.233	2760.94	317.047	1749	9.14	6.093	20.913	1187.5	430
	SAE 40(Avg)	15.1735	180.85	15.233	2754.95	316.813	17515	9.14	6.093	20.92	1200	435.5
1	MoS_2	15.123	179.648	15.27	2743.23	310.609	1729	9.162	6.108	20.71	1168.75	426
2	MoS_2	15.16	180.528	15.163	2737.41	313.453	1736	9.098	6.065	20.703	1187.5	434
	$MoS_{2\,(Avg)}$	15.1415	180.088	15.2165	2740.32	312.031	17325	9.13	6.0865	20.7065	1178.13	430
1	S.P	15.167	180.695	15.213	2748.97	290.484	1608	8.528	6.685	20.073	1075	391
2	S.P	15.163	180.599	15.237	2751.73	288.719	1599	8.542	6.695	20.24	1060	385
	S.P (avg)	15.165	180.647	15.225	2750.35	289.602	16035	8.535	6.690	20.1565	1067.5	388

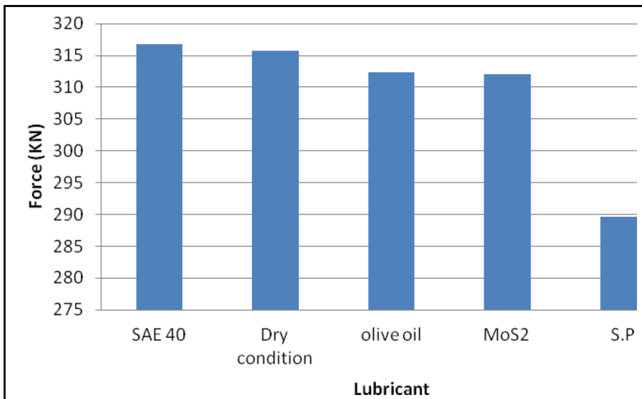

Fig. 2. The Required Force for Producing 40% Reduction in Height in Die Steel, D2, Specimens.

Table 3 shows the results obtained for the different lubricants used with stainless steel. Similarly, it can be seen from the results of Table 3that for stainless steel, the superplastic tin- lead alloy, S.P, is the most effective lubricant among the different used lubricants, as reflected by the minimum final height,

TABLE 3
SUMMERY OF THE RESULTS OBTAINED FOR STAINLESS STEEL

maximum deflection, being 6.645 mm produced under the effect of 172.4 KN, as compared to 177.86 to 205.73 KN for the other different lubricants on stainless steel, i.e. reducing the force by a minimum of 4.1% and a maximum of 19.6%. The arrangement of these lubricants, regarding the required force on stainless steel specimens, is shown in the histogram of Fig. 3.

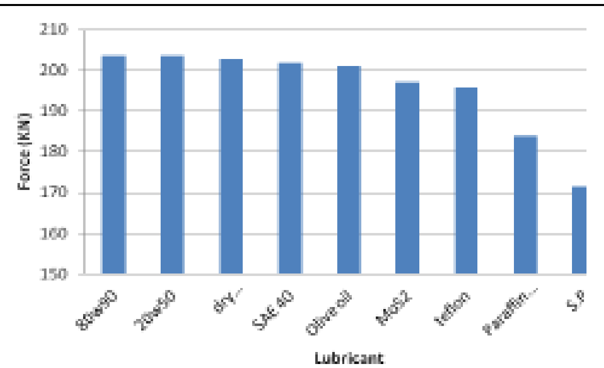

Fig. 3. The Required Force for Producing 40% Reduction in Height in Stainless steel Specimens.

3.1 Evaluation of different lubricants based on the specific energy consumed

In this section, the specific energy i.e. (wP+ wF +wR)/volume consumed by each material for different lubricants for comparing the effectiveness of each lubricant and for determining the most effective lubricant, within the tested lubricants, for each workpiece metal in the free upsetting test. Die steel, D2, workpiece material. As discussed in the previous section, the most effective lubricant is the superplastic tin-lead alloy, S.P as indicated from the results of Table 2, regarding the force required. Similarly, it can be seen from the table that using S.P as lubricant consumed the least amount of specific energy for producing the same deformation in the D2 specimens, with an average minimum difference of 10.8% and average maximum difference of 14.4%. Regarding the effectiveness of other lubricants, they are arranged regarding their effectiveness with respect to S.P are as follows: MoS2, olive oil, SAE 40 and finally the dry condition. This arrangement is shown in Fig. 4.2

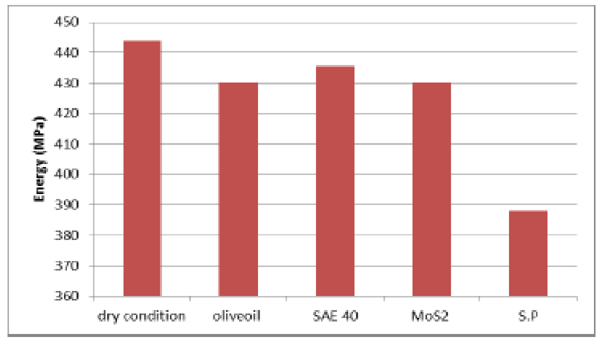

Fig. 4. The Consumed Energy / Unit Volume for Producing 40% Reduction in Height in Die Steel, D2, Specimens..

3.2.1 Stainless steel workpiece material

As discussed in the previous section, the most effective lubricant is the superplastic tin-lead alloy, S.P as indicated from the results of Table 3, regarding the force required. Similarly, it can be seen from the table that using S.P as lubricant consumed the least amount of specific energy for producing the same deformation in the stainless steel specimens, with an average minimum difference of 5.6% and average maximum difference of 24.3%. Regarding the effectiveness of other lubricants, they are arranged regarding their effectiveness with respect to S.P are as follows: Paraffin wax, teflon, MoS2, SAE 40, olive oil, 20W50, the dried condition and finally 80W90. This arrangement is shown in Fig. 5.

3.3 Evaluation of the effectiveness of lubricants based on the amount of barreling produced in Similar Specimens

In this section, the amount of barreling produced in identical specimens of the same material lubricated with one lubricant in each test after free upsetting for die steel, D2, and stainless steel. The maximum diameter in each of those two materials was considered and also the projection of the sectioned specimens across their diameters and tracing their profiles at magnification of 10X using the contracer. The maximum obtained diameter as measured are shown in Table 4. It can be seen from this table that the smallest value of diameter was obtained on specimens lubricated by S.P, in case of die steel D2 and stainless steel, with a minimum difference of 46.15% and a maximum difference of 58.82 on die steel D2 when using MoS2 and SAE 40 respectively. Furthermore, regarding the minimum and maximum values were 33.3% and 60% in case of using MoS2 and olive oil as lubricants respectively. It is worth mentioning in this respect that when using 20W50, 80W90, paraffin wax and teflon lubricants with die steel, D2, the specimens fractured during the upsetting test.

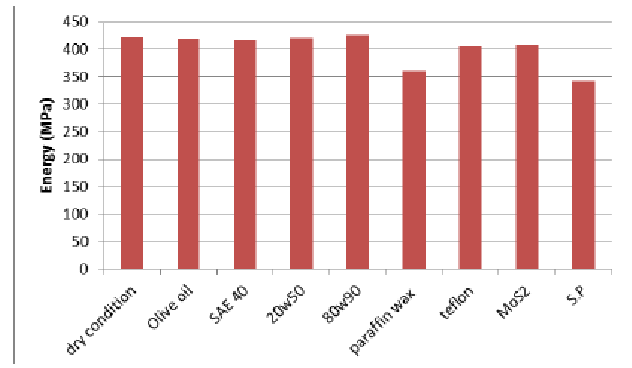

Fig. 5. The Consumed Energy / Unit Volume for Producing 40% Reduction in Height in stainless Steel Specimens

On the whole, it can be concluded that the use of S.P as solid lubricant is the most effective lubricant among the other lubricants. This is explicitly indicated in figures 6 and 7. Die steel, D2. It can be seen from Fig. 6 (a) to (e) inclusive, which indicate the amount of barreling after compression for identical D2 specimens for using S.P, SAE 40, olive oil and the dry condition, and for MoS2 respectively. For the three lubricants, the amount of barreling is almost the same and slightly less

TABLE 4
THE EFFECT OF DIFFERENT LUBRICANTS ON THE AMOUNT OF BARRELING IN THE TWO MATERIALS

Material Barreling / Lubricant	Die steel, (D_2) mm	Stainless steel (mm)
Dry condition	0.80	0.70
Olive oil	0.75	0.75
SAE 40	0.80	0.70
20W50	-	0.80
80W90	-	0.70
Paraffin wax	-	0.60
Teflon	-	0.40
MoS_2	0.65	0.45
S.P	0.35	0.30

than in the case of the dry condition. However, compared by the amount of barreling produced when using S.P lubricant it can be seen from the tracing of the final profiles that there is practically no barreling produced as it can be seen from figure 6(a) that the parallel planes remained parallel and the perpendicular planes remained perpendicular, i.e. homogenous deformation. This explains why D2 specimens lubricated by S.P consumed less specific energy as redundant work practically does not exist

3.3.1 Stainless steel

Figs. 7 (a) to (i) inclusive, shows the amount of barreling traced by the contracer at X5 produced on stainless steel specimens after compression using the following lubricants: Olive oil, MoS2, 20W50, the dry condition, teflon, 80W90, SAE 40, Superplastic tin-lead alloy, and paraffin wax respectively.

It can be seen from these traces that S.P has given the least amount of barreling, Fig. 7, as compared to the other lubricants, followed by teflon, MoS2, paraffin wax, SAE 40 which gave almost the same amount of barreling as in the case without using lubricant and when using 80W90, followed by olive oil and finally 20W50.

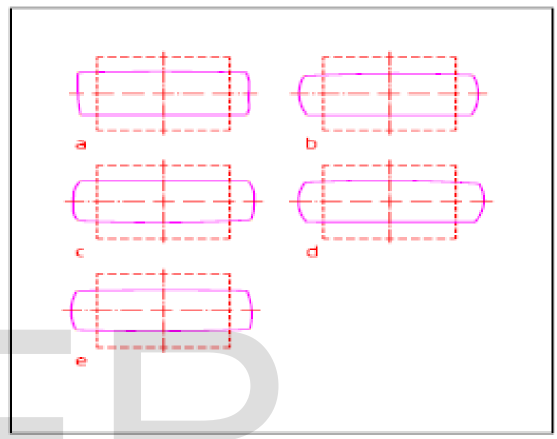

Fig. 6. The Original and Final Profiles of Sectioned Die Steel, D2, Specimens Using Different Lubricants where a, b, c, d, and e for Superplastic Tin-lead, SAE 40, olive oil, dry condition, and MoS2 Respectively

4 CONCLUSIONS

From the results obtained in this work the following points may be concluded:

1. Superplastic tin- lead alloy has proven to be an effective solid lubricant in free upsetting forging with die steel, D2, and stainless steel as compared to the other seven different lubricants used in this paper, within the experimental limitations.
2. Three criteria used for evaluating the different lubricants namely:

(i) Consideration of the amount of reduction in height in identical specimens and of the same material under the same compression force as a criterion. The lubricant which results in the maximum reduction in height is the most effective, and found to be the S.P.

(ii) The energy consumed in producing the same reduction in height in similar specimens as a criterion. The specimen with a lubricant which consumes the minimum energy is the most effective and so on. The specimen lubricated with S.P consumed the minimum energy.

(iii) The amount of barreling produced in identical specimens of the same dimensions of the same material in the free upsetting test under the same reduction in height as a criterion for assessing the effectiveness of the different lubricants. The lubricant which produces the least amount of barreling is the most effective, these criteria have proven to be successful and very reliable.

3. Among the eight different lubricants used in this work with stainless steel, their effectiveness in sequence, starting from the best, were found to be: superplastic tin- lead alloy, S.P alloy, paraffin wax, teflon, MoS2, SAE 40, olive oil, 20W50, and 80W90.

The arrangement sequence regarding the effectiveness of the different lubricants varied depending on the workpiece material for the different lubricants but S.P remained the most effective lubricant for all the tested workpiece materials.

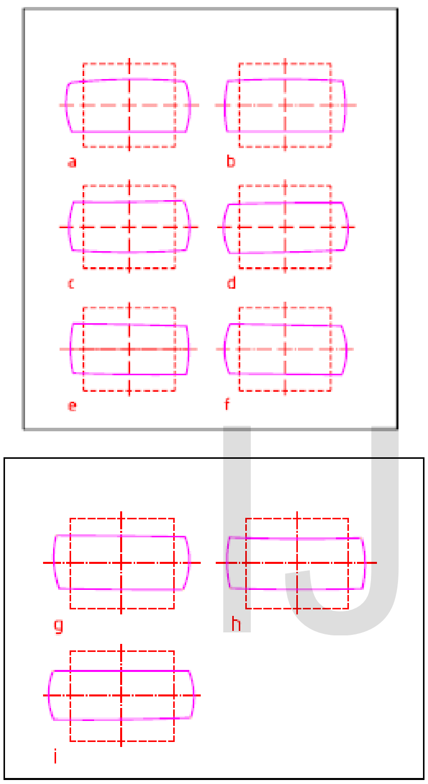

Fig. 7. The Original and Final Profiles of Sectioned Stainless Steel Specimens Using Different Lubricants where a, b, c, d, e, f, g, h, and i for Olive Oil, MoS2, 20W50, the Dry Condition, Teflon, 80W90, SAE 40, Superplastic Tin-lead Alloy, and Paraffin Wax Respectively

ACKNOWLEDGMENT

The first author is grateful to the Applied Science Private University, Amman, Jordan for the financial support granted to this research (Grant No.DRGS-2015)

ACKNOWLEDGMENT

The first author is grateful to the Applied Science Private University, Amman, Jordan for the financial support granted to this research (Grant No.DRGS-2015)

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