Tool, lubricant and process parameters investigation to form an AA 3003-H12 sheet by single point incremental sheet forming process

R.BENMESSAOUD*, M.RADOUANI, Y.AOURA, B. EL FAHIME

Abstract— The present study investigates the tool, lubricant, lubrication method and process parameters in order to form pyramidal parts with good surface finish and structural integrity, from an AA 3003-H12 sheet, by single point incremental sheet forming process. The process parameters studied are the vertical step, the feed rate, the tool rotational speed, tool diameter, lubrication and the distance of the forming area from edges. Geometric profiles and thickness distributions across vertical median sections of the final parts are studied. Rectangular blanks are used to form truncated quadrangular pyramids, using the same contour tool path for all experiments. Experimental results indicate that a specific polished steel tool with a proper lubricant, lubrication method and process parameters values are suitable to obtain reasonably good surface finish and acceptable structural integrity. The vertical step, feed rate, spindle speed, tool diameter and lubricant type do not affect the final geometric profile and thickness distribution. Internal surface roughness increases with increase in tool rotational speed and vertical step, but decreases with increase in tool diameter. The increase of feed rate leads to an increase then a decrease of the internal surface roughness. Coating the sheet-blank with a sufficiently thick film of pure mineral lubricant is appropriate to obtain a reasonably good surface quality and to avoid formed part structural defects. The study also demonstrates the possibility to optimize the part quality, its production time and cost by an accurate control of process variables.

Index Terms—Aluminium, Incremental, Roughness, Surface, Lubrication, Sheet, Forming, Method.

— ◆ —

1 INTRODUCTION

Single point incremental forming (SPIF) is an emerging process with great ability to manufacture complex sheet parts without making use of specific tooling components. This makes it very suitable for rapid prototyping and customized products. In this process, a steel rod with a hemispherical shaped end, is used as a forming tool to cross a pre-defined contour, and produces progressively local plastic deformations in a sheet. The time needed to form components with SPIF is very long compared to other conventional processes. For this reason, it is recommended for the low series production industries. The production of low volume batches is nowadays required by many industrial sectors such as rapid prototyping and automotive [1]. One of the important requirements for commercializing this technique is the capability to produce new parts with desired surface finish and structural integrity. The aluminium alloy AA 3003-H12 is widely used as a general purpose for moderate-strength applications that require a good workability (stamping, chemical equipment, fan blades,...)[2]. Very recently, Khalatbari et al. [3] formed conical parts from an AA 3003-H12 sheet and investigate the process variables effect on material formability. Conical and pyramidal parts are the most standard geometries used in the literature to investigate the SPIF process. They include the most common combinations of curves and angles that can be found in the SPIF parts. Pyramidal parts suggest tool path with sharp angles, while conical parts suggest the use of path with great curvative radii. Since the process mechanic is strongly related to the forming tool path [4], the part quality (Structural integrity, surface roughnes,...) is related too. Minutolo et al.[5]conduct experiments and numerical analysis to evaluate the formability for the two geometries,by means of maximum slope angle.They conclude that the maximum drawing angle of a pyramidal part (63°) is lower than that of a conical part (67°). They also demonstrate that the crack localisation depends on the part geometry (cone or pyramid). The SPIF process of pyramidal components has been the subject of many studies[6],[7],[8],[9]. However, it is still unknown how to produce such parts from an AA 3003-H12 sheet. In fact, the sheet material is well known to have a strong effect on part quality (formability,structural integrity, geometric precision,...)[4].Therefore, an experimental study that enables successful forming of pyramidal parts in AA 3003-H12 is vital for the knowledge of SPIF.A comprehensive review of the literature may reveal that the selection of the forming tool, lubricant and process parameters and applying an effective lubrication method are vital for producing sheet-metal parts with good surface finish and acceptable structural integrity. Hussain et al. [10] indicate that an appropriate selection of lubricant and tool is very important to produce successfully sheet-metal parts with a good surface quality. They propose a lubrication method in combination with a tool and specific

- *Radouane BENMESSAOUD is a PhD student at the National Higher School of Engineering (Crafts and Technologies, ENSAM Meknès - Moulay Ismail University, Morocco).E-mail: radouane.benmessaoud@gmail.com*
- *Mohammed RADOUANI is a professor at the National Higher School of Engineering (Crafts and Technologies, ENSAM Meknès - Moulay Ismail University, Morocco). E-mail: m.radouani@ensam-umi.ac.ma*
- *Youssef AOURA is a professor at the National Higher School of Engineering (Crafts and Technologies, ENSAM Meknès - Moulay Ismail University, Morocco). E-mail: y.aoura@ensam-umi.ac.ma*
- *Benaissa EL FAHIME is a professor at the National Higher School of Engineering (Crafts and Technologies, ENSAM Meknès - Moulay Ismail University, Morocco). E-mail: b.elfahime@ensam-umi.ac.ma*

Corresponding author:R.BENMESSAOUD;
E-mail: radouane.benmessaoud@gmail.com

lubricants and investigate the range of process parameter values where the method is effective. Matsubara [6] demonstrates that the burnishing effect and the surface texture of the tool are important for the part surface obtained by SPIF process. Kim and Park [7] use a ball tool, without lubrication, to form an aluminium alloy (1050) sheet and indicate that the fracture occurs for high friction levels. Wilson [8] emphasizes that the lubrication regime has a strong effect on the frictional conditions as well as on the other factors such as tooling wear rates and product surface finish in sheet metal forming operation. When a pyramidal part can be formed from an AA 3003-H12 sheet with an acceptable structural integrity and a reasonably good surface roughness, it will be very important to investigate the process variables effect on the formed part characteristics. Such study may help to master the process parameters and consequently make it possible to optimize some process and product characteristics such as surface finish, time-to-market, and production cost. Many studies explore the effect of process parameters[9],[10],[11],[12]. Cerro et al. [1] demonstrate that an optimization of the formed parts quality is possible, by studying the effect of process parameters (Feed rate, forming force, and tool trajectory) on the formed shape characteristics (Surface finish, thickness,...). Jeswiet et al. [4] indicate that the processing time can be reduced by a control of vertical incremental depth while satisfying a reasonably good surface finish. Time-to-market which is very important in the commercialization of SPIF components depends mostly on processing time. The production cost in the SPIF process depends on many parameters (energy consumptions, processing time, lubricants, tooling, sheet and tool materials,...).Tooling design depends on forming forces which are related to feed rate, tool rotational speed, tool diameter, vertical step size and lubrication as described in [4]. Higher forming forces in SPIF process require robust tools and consequently a higher production cost. Even if the increase of vertical step size induces a decrease in the processing time, the forming forces increases [4]. Besides, forming forces variation affects the mechanical work requirements at the tool [13], which may affect energy consumptions. Tool rotational speed variation affects forming forces [14] and energy consumption [13]. Feed rate variation affects the forming forces, processing time, and energy consumptions. Lubricant cost increase induces an increase in the production cost. Tool diameter can be increased to allow larger vertical step sizes and consequently lesser production time [4], but the material cost will be greater which affects the production cost. Time-to-market which is very important in the commercialization of SPIF components depends on processing time.

In this paper, an experimental study is carried out, firstly to form pyramidal parts from an AA 3003-H12 with a reasonably good surface finish and structural integrity and secondly to investigate the process parameters effect on the produced part characteristics. Two mineral lubricants along with a polished tool in steel Z160 are used to form quadrangular pyramids in AA 3003-H12. A novel lubrication method for incremental sheet forming of parts is proposed. Rectangular blanks with and without a thin layer of lubricant are used to investigate the tool, lubricant, lubrication method and process parameters. Vertical step size, tool rotational speed, feed rate, tool diameter, lubrication and the distance of the forming area from the edges are the process variables considered. A simple and rapid method is used to generate and implement the contour tool path spatial coordinates in the CNC milling machine. The thickness and geometric profile across vertical median sections of the formed parts are ascertained and analyzed. Qualitative observations and quantitative measurements of surface finish are made.

2 MATERIALS AND METHODS

An experimental setup for the SPIF process is designed and fabricated to conduct the experiments (Fig.1). Forming tools are fabricated and polished with height precision level.

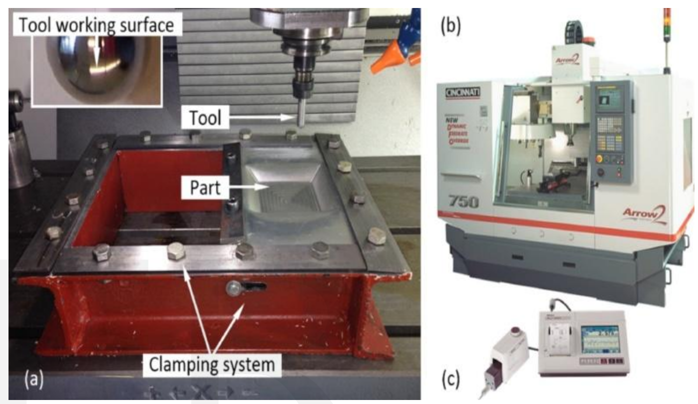

Fig. 1. (a) Experimental setup for SPIF experiments, (b) Three-axis milling machine for SPIF tests, (c) Roughness measuring device

Truncated pyramids are formed for the study (Fig.2).Preliminary experiments are conducted, and based on the results of these experiments a serie of tests are carried out (Table 1). Material, sheet thickness and fixturing are held constant. The frustum of the pyramid wall angle remains constant by varying the number of cycles and horizontal step size. Preliminary tests are also made to verify the possibility of making parts by SPIF in the range of parameters values with the lubricant (Table 2) and the tool selected. The tools used in all experiments are fabricated from working tool steel Z160 where hardness is equal to 75 HRA. A control process of the tool surface is carried out. The tool keeps its initial geometry, remains burnished and not warmed after the experiments[10],[6]. Contour tool paths are used for all experiments; after shifting the first coil with a vertical step size, the tool moves horizontally with a horizontal step size, and then it shifts to the next loop. The drawing depth is fixed at 20 mm. Dimensions of the sheet blank and the target geometry are illustrated in Fig.2. An advanced computer application is developed under Eclipse IDE to generate the spatial tool coordinates under file format, which is easily and rapidly implemented into CNC milling machine

International Journal of Scientific & Engineering Research, Volume 7, Issue 11, November-2016
ISSN 2229-5518

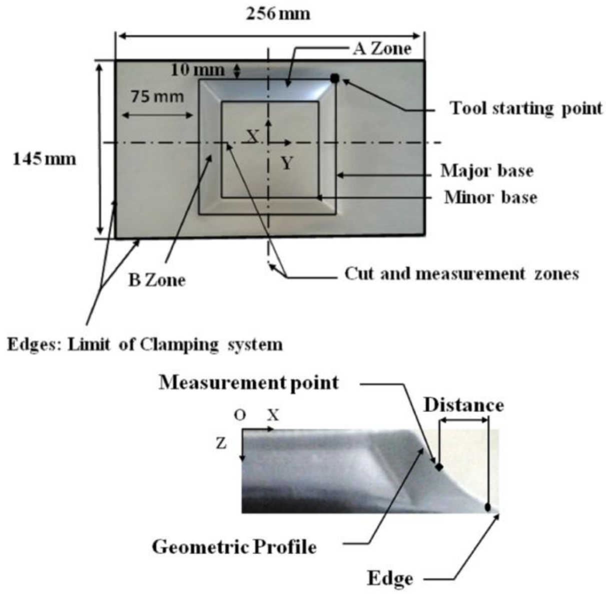

Fig.2 Pyramidal shape for testing forming parameters

TABLE 1
SPIF **E**XPERIMENTAL **T**ESTS

Part	S (rpm)	F (mm/min)	Tool diameter (mm)	Δ_x (mm)	Δ_y (mm)	Δ_z (mm)	Cycles number	Lubricant
1	6283.18	500	10	1	1	1	20	Oil 1
2	6283.18	500	10	2	2	2	10	Oil 1
3	6283.18	500	10	0.5	0.5	0.5	40	Oil 1
4	6283.18	300	10	1	1	1	20	Oil 1
5	6283.18	50	10	1	1	1	20	Oil 1
6	3769.91	500	10	1	1	1	20	Oil 1
3	1256.63	500	10	1	1	1	20	Oil 1
8	6283.18	500	10	1	1	1	20	None
9	6283.18	500	10	1	1	1	20	Oil 2
10	6283.18	500	15	1	1	1	20	Oil 1

An aluminium alloy blank (AA3003-H12) whose thickness is 1.05 mm, is used for the study. Limits of the clamping area are drawn before the release of the part from clamping system. Then, two center lines along (OX) and (OZ) directions are drawn after releasing (Fig.2). The part is cut at the first drawn line along (OX). A Dial Gauge (±0.02 mm) is used to measure depth at the scribing points relative to the flat outer surface of the cut part as described in Fig.2. At least, three measurements are done, and the average value is adopted. The same method is used to measure depth at the drawn line along (OY). Thickness is measured relative to the flat outer surface of the cut part using a Dial Gauge indicator (±0.01 mm).For each formed part wall; small rectangular flat sections are cut from different areas. The roughness device (Surftest SJ-410, Make: Mitutoyo) (Fig.1) gives the roughness parameters values (Ra, Rq, and Rz) for each specimen. Then, the average value of each parameter is adopted.

TABLE 2
KINEMATIC **V**ISCOSITY AND **D**ENSITY OF **O**ILS

	Oil 1 (Shell Tellus oil	Oil 2 (Sell Dro-
Kinematic viscosity at 20 ° (mm^2 /s)	32	40.4
Density at 15 °	875	930

3 RESULTS AND DISCUSSION

3.1 Geometric profile

With reference to Fig.3 (a-e), it can be noted that vertical step size, feed rate, spindle rotational speed, tool diameter, lubricant type have no influence on the final geometric profile. In fact, the significant heating effect caused by the relative motion between tool and blank affects the mechanical properties of the sheet [15] ,this modify its deformation behaviour, which leads to significant springback diference,and consequently greater geometric deviation. When the tool rotational speed variation is not significant, the springback difference is negligible, which induce similar geometric profiles. The insignificant heating effect generated by sliding friction [4]when the feed rate increases, induces also similar geometric profiles. The insignificant effect of step size variation on the final geometric profiles can be explained by the following reason: when vertical step size increases, overlaps between neighboring tool paths will be different. Residual stresses due to cyclic plastification and unloading will be different but not significant to cause deviation from the target geometry. The increase of tool diameter may cause an increase in overlaps between neighboring paths, which indicates again that residual stresses are not sufficient to cause deviation from the target geometry.
The same geometric profiles obtained by the two oils can be explained by the specific properties of lubricants that minimize, in a similar way, the effect of heating due to relative motion between tool and sheet, which induces less springback as described previously.
Forming without lubrication has a negative effect on the final part. Cracks, necking, and failure are present in the formed part in this case (See discussion of lubrication effect on surface finish). Regarding the edge influence on the final geometric profile, Fig.3 (f) illustrates geometric profile evolution of the part, related to the first test, with the distance from the blank center (Point O), across the vertical median sections, for the two directions (OX) and (OY) (Fig.2). It can be noted that geometric precision is greater in A zone which is near the clamped region compared to B zone. In fact, when the distance of the forming zone from edge decreases, the deformation area is restricted which makes the stress more localised beneath the forming tool, hence less springback, and consequently greater geometric precision.

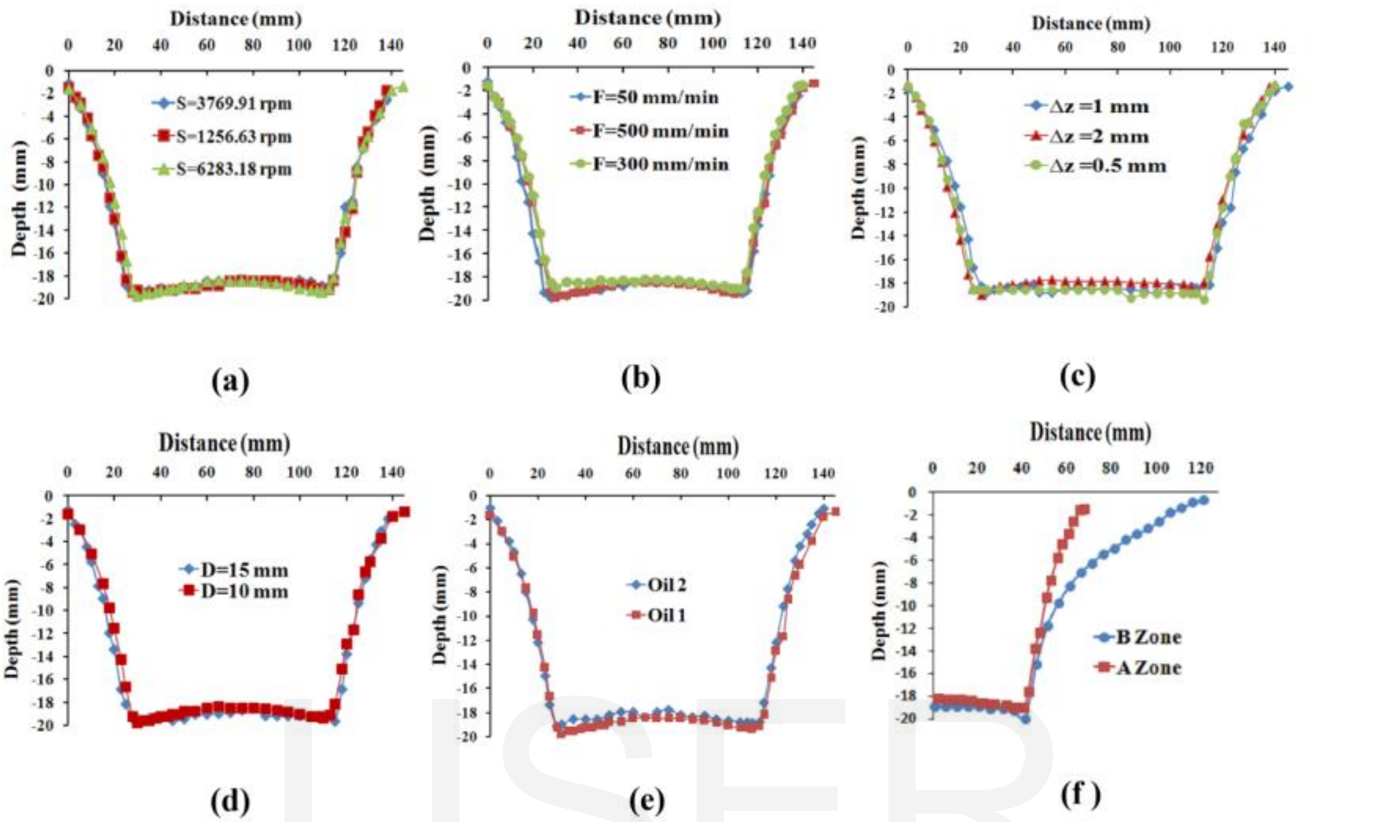

Fig.3. Geometric profiles of the parts produced with: (a) Spindle speed tests (b) Feed rates tests (c) Incremental depth tests (d) Tool diameter tests (e) Lubrication tests (f) Distance of the forming area from edge

3.2 Thickness distribution

The vertical step size, feed rate, tool rotational speed, tool diameter, and lubricant type have practically no influence on the final thickness distribution (Fig. 4 (a-e)). No crack, failure or necking is observed in the parts produced with lubrication (See section 3.2.5).The negligible effect of vertical step size and tool diameter is likely due to the fact that their variation is not significant enough to cause significant thickness variation. Indeed, local forming area size is related to the previous parameters values, a variation of theses ones induces a variation in stress distribution at the tool/sheet contact interface [16], which affects the plastic deformation, and consequently the sheet thickness. With regard to the negligible effect of feed rate, tool rotation speed, and lubricant type on the final thickness distribution, it can be explained by the fact that heating generated by friction is not significant enough to cause significant variation in stress distribution at the tool/sheet contact interface, which entails negligible thickness variation.

In order to compare the experimental and theoretical results , the sin law equation is used [4].Calculated value obtained using the previous relation is 0.74 mm that matches well with the thinning band value obtained.

The sin law equation indicates that sheet thickness depends only on the wall angle which is fixed during the experiments. Except the part produced without lubrication and which is defective, obtained results are in agreement with this relation. In order to ascertain the edge influence on the final thickness distribution, thickness is measured according to the (XY) plan. The thickness evolution with the distance from the sheet center (O) (Fig.2), for the two zones, is illustrated in Fig.4 (f). The sheet thinning is greater in A zone compared to B zone.

In fact, zone A which is near the clamped region, undergoes more stretching compared to B zone which undergoes more bending. The insignificant influence of process variables on the geometric profiles and thickness distributions makes it possible to produce the same part with good structural integrity using various combinations of parameters values. The processing time can be reduced by an increase of vertical step size. However, the production cost can increase due to higher forming forces. Hence, it will be possible to optimize processing time and production cost while ensuring the same geometry and a good structural integrity.

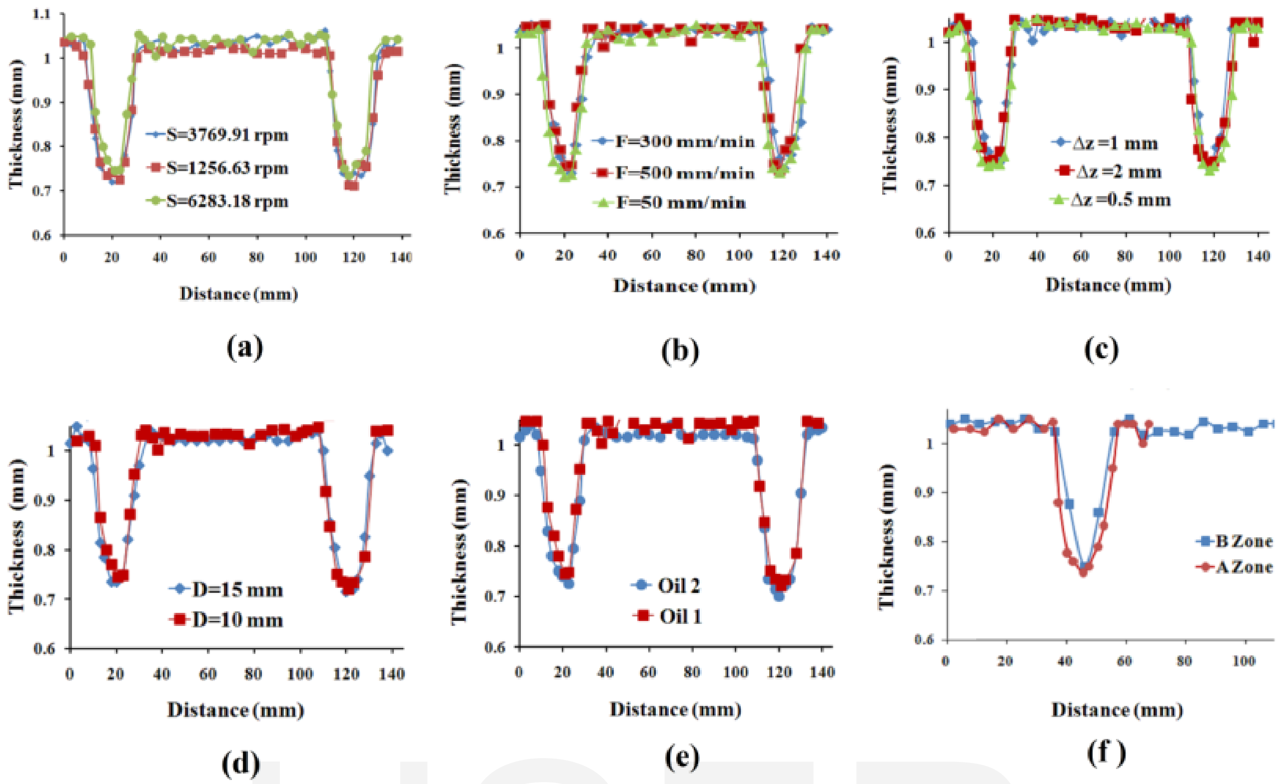

Fig.4. Thickness distribution of the parts produced with: (a) Spindle speed tests, (b) Feed rates tests, (c) Incremental depth tests, (d) Tool diameter tests, (e) Lubrication tests (f) Distance of the forming area from edge

3.3 Surface finish

3.3.1 Step size

Using greater step size creates more distinctive cusps at the internal and external surface (Fig. 5(a-f)) due to the fact that overlaps between neighboring tool paths are reduced [17]. Bhattacharya et al. [17] indicate that more work material comes in contact with the tool when vertical step size increases ,which induces more stretching and less bending . They report that the formability increase is mainly due to the simultaneous stretching and bending. When stretching prevails over bending, the tendency of the material to crack increases. Accordingly, the obtained part formability decreases with increase in vertical step size The surface roughness parameters Ra, Rq , and Rz increase slightly with an increase of incremental depth for A zone and B zone(Fig.5 (g)). The surface roughness increase can be explained by the same mechanism described previously; the decrease in overlaps between neighboring paths. Average roughness value for A zone is less than 9 % of these obtained in B zone which indicates the insignificant influence of edges on surface finish in the range of values considered. This is likely due to the following reason: zone A is near the clamped region (Fig.2), when tool penetrates with a vertical step size p, deformed area depth is greater compared to B zone because of less springback (Fig.6).The deformed area depth in A zone is greater, and overlap of the neighboring paths happens down. The deformed area depth in B zone is smaller, and overlap happens on top. The first aspect prevails in this case, and average roughness in A zone, with reference to Eq. (1), is smaller than the one of B zone. Average roughness values obtained are compared with reference values (ASME B46.1 (2002) standard). It is verified that the roughness values of the formed surfaces are in the range that qualifies conventional forming processes (cold rolling, drawing...).

In order to compare obtained results with the ones predicted by the models available in the literature, a summary is given in Table 3. Using estimation models for surface roughness Ra established in, experimental values obtained in this work are lesser. This may be attributable to the fact that the prediction models do not consider the lubricant, feed rate, and tool rotational speed effect in their formulations.

TABLE 3

COMPARISON OF **A**VERAGE **R**OUGHNESS **O**BTAINED WITH **A**VAILABLE **R**ESULTS IN **L**ITERATURE

Part	Ra (µm) (A Zone)	Ra (µm) (B Zone)	Ra (µm) (Litterature)
1	1.64	1.76	1.939 **[17]** (Prediction model)
			2.53 **[18]** (Prediction model)
2	1.88	2.08	3.79 **[18]** (Prediction model)
3	1.55	1.69	2.64 **[17]** (Prediction model)
10	1.376	1.015	1.91 **[18]** (Prediction model)

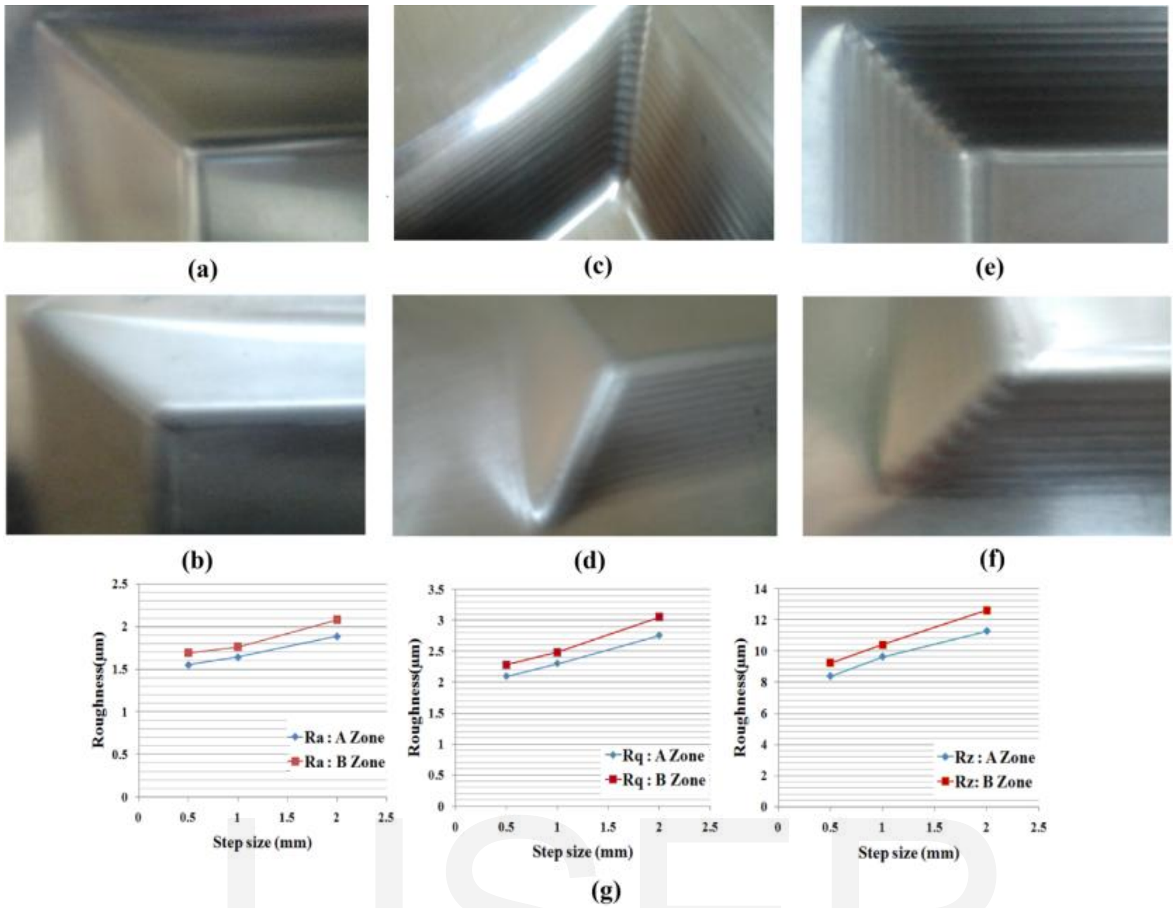

Fig. 5.Surface finish of the parts produced by step size tests (a, b) internal and external surface (0.5 mm) ;(c,d) internal and external surface (1 mm) ; (e,f) internal and external surface (2 mm); (e) roughness parameters (Ra,Rq, and Rz) of internal formed surface.

With reference to Fig.5 (g), it can be seen that the surface roughness can be controlled by changing the vertical step size. The processing time can be reduced by the increase of vertical step size while the surface finish remains good. On the other hand, the surface finish can be improved by the decrease of vertical step size. Thus, an optimization of the part quality (structural integrity and surface finish), its production time and cost, will be possible, by an accurate selection of the vertical step size.

$$R_a = \frac{\int_0^{\frac{p}{2}} |y(x)-y|dx}{p/2} \quad (1)$$

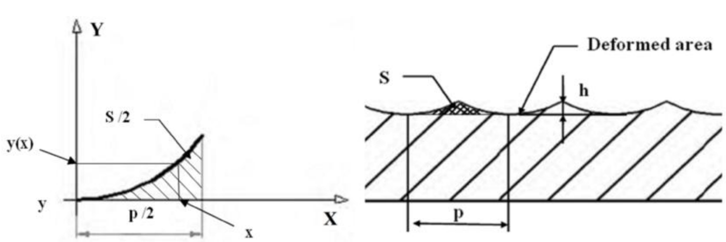

Fig.6.Roughness profile for the theoretical [18]

3.3.2 Feed rate

The feed rate does not affect significantly the external and internal surfaces finish (Fig.7 (a-f)). Distinctive cusps are produced with an increase of advancing speed (300-500 mm/min). This can be explained by the following reason: when feed rate increases, the heating of the sheet, generated by sliding friction [4], increases. With reference to Fig.6, the deformed area depth is greater due to less springback, the overlap between neighboring paths happens on top which induces more distinctive cusps.

The surface roughness parameters (Ra, Rq, and Rz) increase slightly then decrease in the range of feed rates considered (Fig.7(g)). Average surface roughness increases first with 7 %, which is not significant, then decreases. Otherwise, the decrease of average surface roughness is significant (more than 20 %).

The surface roughness decrease with increase in feed rate can be explained by the following reason: As the feed rate decreases, the number of tool revolutions per mm of displacement increases, relative motion between tool and blank at the contact area increases, temperature increases, and friction is reduced [14], which affects the sheet behaviour (such as hardening).

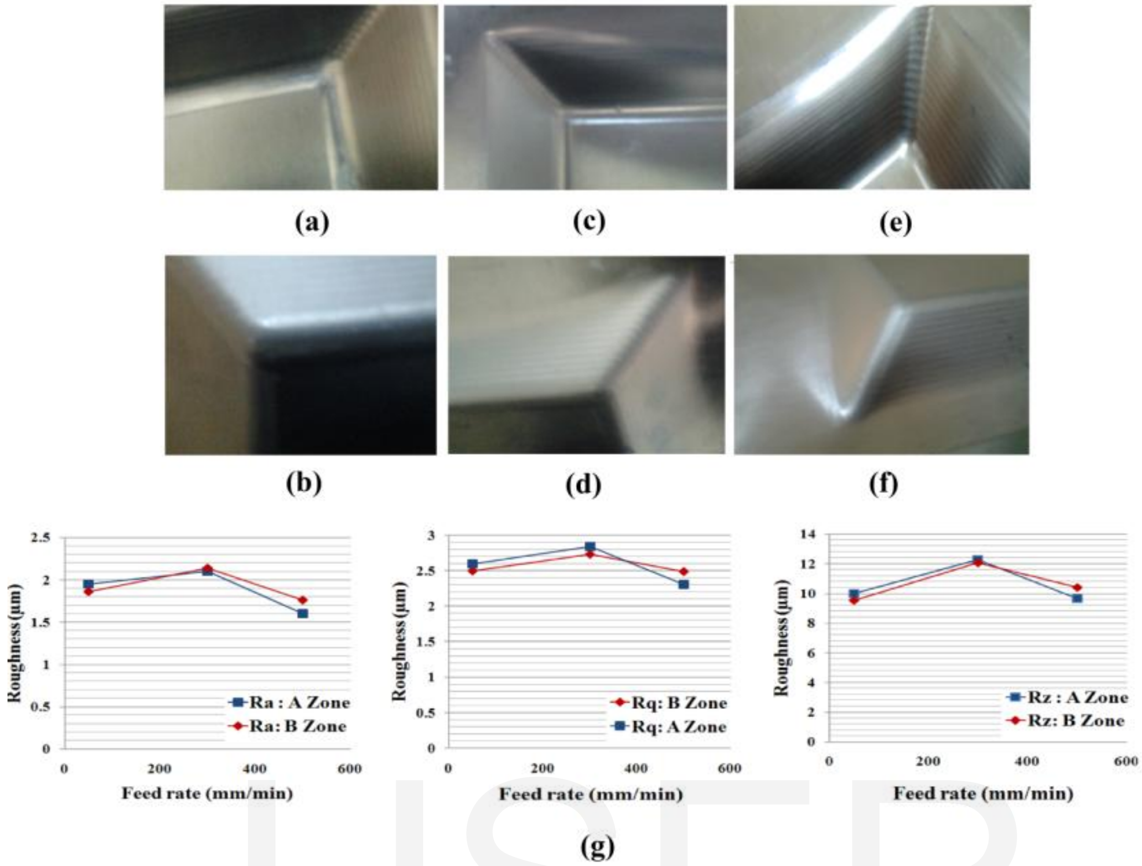

Fig.7.Surface finish of the parts produced by feed rate tests (a, b) internal and external surface (50 mm/min) ;(c,d) internal and external surface (300 mm/min) ; (e,f) internal and external surface (500 mm/min); (e) roughness parameters (Ra,Rq, and Rz) of internal formed surface.

For an incremental displacement (Fig.6), deformed area undergoes springback, p remains fixed, but the obtained profile induces greater S, hence greater average surface roughness (Eq.1). The insignificant variation of roughness with the increase of feed rate is may be due to the fact that the heating generated is not significant enough to cause a significant deviation between the obtained roughness profiles (Fig.6).The increase of temperature and decrease of surface roughness indicates that the heat generation increase caused by the increase of feed rate does not affect significantly the lubrication property of the lubricant used. In fact, the increase of heating induces thermal degradation of lubricant [19], but contact pressure decreases, in this case, so that more lubricant nanoparticles are trapped at the contact zone [20], which retains the lubricant efficiency. The same figure indicates that surface roughness difference passing from A zone to B zone does not exceed 10% for the three criteria which indicates the insignificant influence of edges on the surface finish by varying the feed rate. The roughness drop (from B zone to A zone) can be explained by the same mechanism described previously (See section 3.2.1). Average roughness values obtained are compared with reference values (ASME B46.1 (2002) standard). It is verified that the roughness values of the formed surfaces are in the range that qualifies conventional forming processes.

Feed rate can be increased to reduce the processing time and surface finish while keeping the same geometry and a good structural integrity. However, increasing the feed rate can affect forming forces, energy consumption, etc. This indicates that the part quality (structural integrity and surface finish), its processing time, and its production cost can be optimized if an accurate selection of the advancing speed is done (Fig.7 (g))

3.3.3 Tool rotational speed

The tool rotational speed affects the internal and external surfaces finish (Fig.8 (a-f)).Surface cusps become more distinguished with the increase of tool rotational speed. This is likely due to the following reason: when tool rotational speed increases, the relative motion between blank and tool increases, the heating of the sheet increases due to the increase of friction, which induces more distinctive cusps as explained previously (See section 3.2.2).

Fig.8 (g) indicates that the increase of tool rotational speed induces an increase of surface roughness (Ra, Rq, and Rz). In this case, the roughness may be increased with more than 20 % which is significant.

The surface roughness increase is likely due to the same mechanism described previously; the relative motion between the tool and blank increases with increase of rotational speed, the heating generated increases, which induces greater surface roughness. Surface roughness decrease passing from B zone to A zone is reduced to less than 10 % (See the discussion of vertical step size effect on surface finish for mechanism).

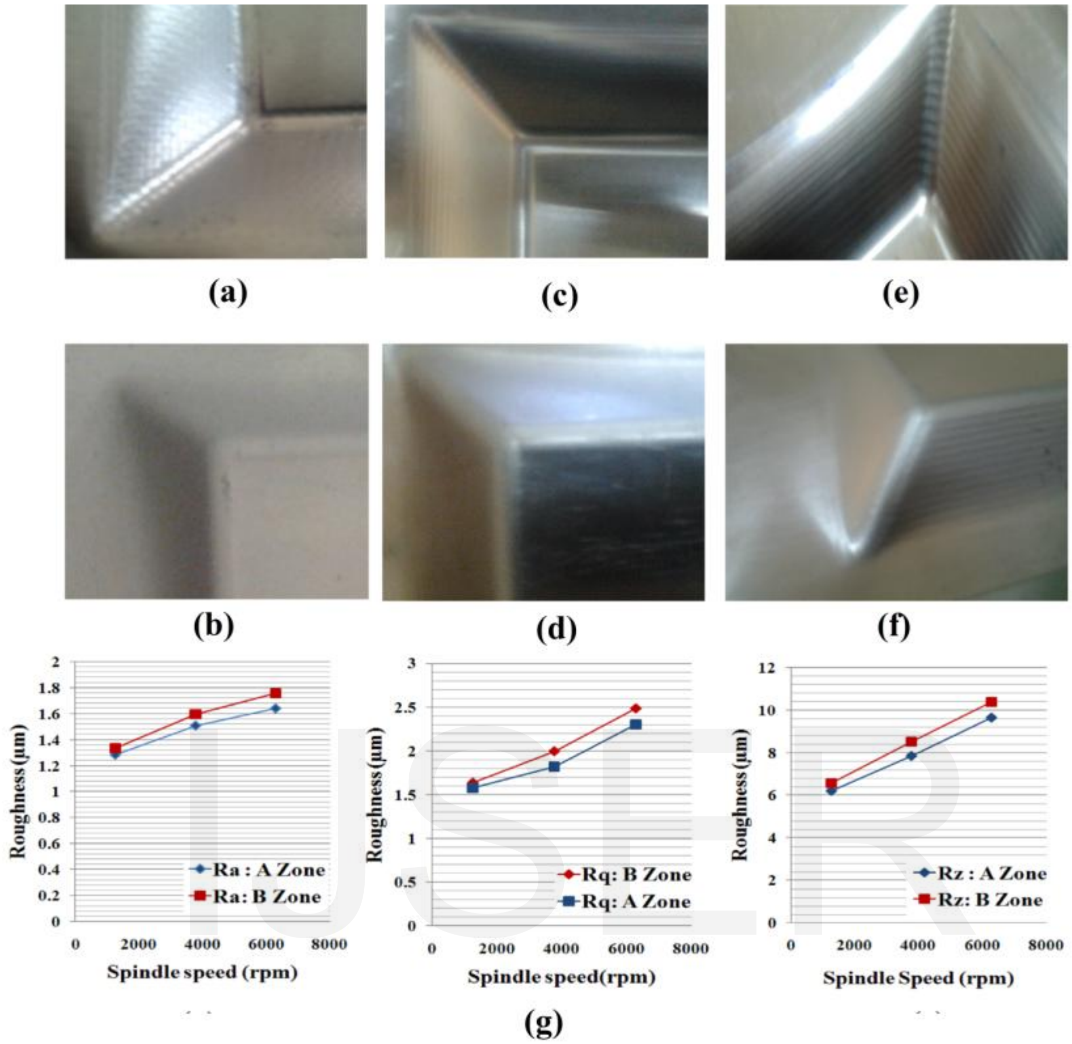

Fig.8.Surface finish of the parts produced by spindle speed tests (a, b) internal and external surface (1256.63 rpm);(c,d) internal and external surface (3769.91 rpm) ; (e,f) internal and external surface (6283.18 rpm);(e) roughness parameters (Ra,Rq, and Rz) of internal formed surface.

Average surface roughness values obtained in this section are compared with those given by the prediction models available in the literature (Table 3), and they were found to be lower. Moreover, the average roughness values of the formed surfaces are in the range that qualifies conventional forming processes (ASME B46.1 (2002) standard).
The tool rotational speed can be decreased to reduce energy consumption and surface quality, while keeping the same geometry and a good structural integrity. However, tool rotational speed variation affects forming forces which can affect production cost.
This indicates that the part quality (structural integrity and surface finish), its processing time, and its production cost can be optimized if an accurate selection of feed rate, in the range of values considered, is done (Fig.8(g)).

3.3.4 Tool diameter

Clear observations of the formed shapes (Fig.9(a-d)) indicate that both internal and external surfaces become indistinguishable using greater tool diameter and distinctive cusps are produced using small tool diameter due to the decrease of overlap between neigboring tool paths [17].When tool diameter increases, the stretching amount increases due to the fact that more work material is in contact with the tool. Therefore, the tendency of the material to crack increases. Accordingly, the part formability increases with the decrease of tool diameter.
Fig.8(e) indicates that the increase in tool diameter induces a significant decrease in the three surface roughness parameters. Using average surface roughness to distinguish the surface finish, this one can be reduced more than 40 % using greater tool diameter for zone B and more than 14 % for zone A.

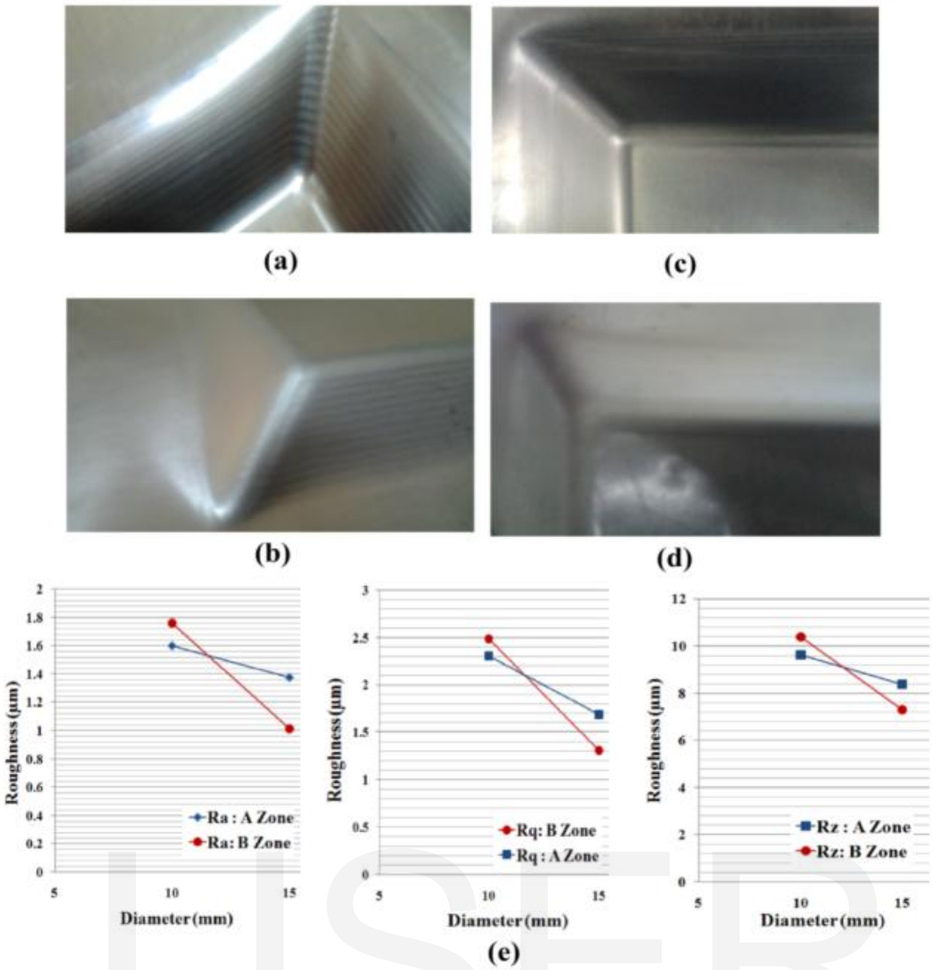

Fig.9.Surface finish of the parts produced by tool diameter tests (a, b) internal and external surface (10 mm); (c,d) internal and external surface (15 mm); (e) roughness parameters (Ra,Rq, and Rz) of internal formed surface.

Decrease of surface roughness in both zones is likely due to the same reason described previously; when vertical step size remains fixed, and tool diameter increases overlap of the neighboring paths happens down, hence less average surface roughness. When using a small tool diameter surface roughness in A zone is lesser than that in B zone. This is likely due to the following reason: for greater tool diameter, deformed area depth is greater in A zone, and overlap happens down. Deformed area depth in B zone is smaller and may be overlap does not happen which induces less surface roughness. Regarding the surface quality of the produced components, it is verified that the roughness values of the formed areas are in the range that qualifies conventional forming processes (ASME B46.1 (2002) standard). These values are also compared with those obtained in literature (Table 3) and found to be lesser. Tool diameter can be increased to reduce the surface roughness or decreased to reduce tooling cost while ensuring the same geometry and good structural integrity. This indicates that an optimization of the product quality (structural integrity and surface finish), its processing time and cost is possible by an appropriate selection of tool diameter.

3.3.5 Lubrication

The lubrication is essential to reduce friction between tool and sheet [10]. During forming operations conducted without lubrication, pasty areas are produced and smoke billows at the tool-sheet contact areas, which indicates an excessive increase of heating. Necking is produced at the bulge areas, which are clearly observed at the external surface (Fig.10 (a) and (b)). The mechanism behind necking is the increase of stretching, caused by tensile stresses, with the increase of heating, while the bulge areas are likely due to the in-plane stresses [21]. This is worth mentioning that the sheet peels off due to excessive contact pressure [21], and the material adheres to tool tip due to heating effect. By using oil 1 with 20% dispersed in water so that that the tool head is immersed in the lubricant during the forming operation, two problems still persist; the material adherence to the tool head and blank erosion. These ones are jumped by using oil 1 without water during preliminary tests for different values of process variables. The blank surface is coated with oil 1 at a level of 0.5 mm approximately. This one adheres more to surface due to its great viscosity [10].

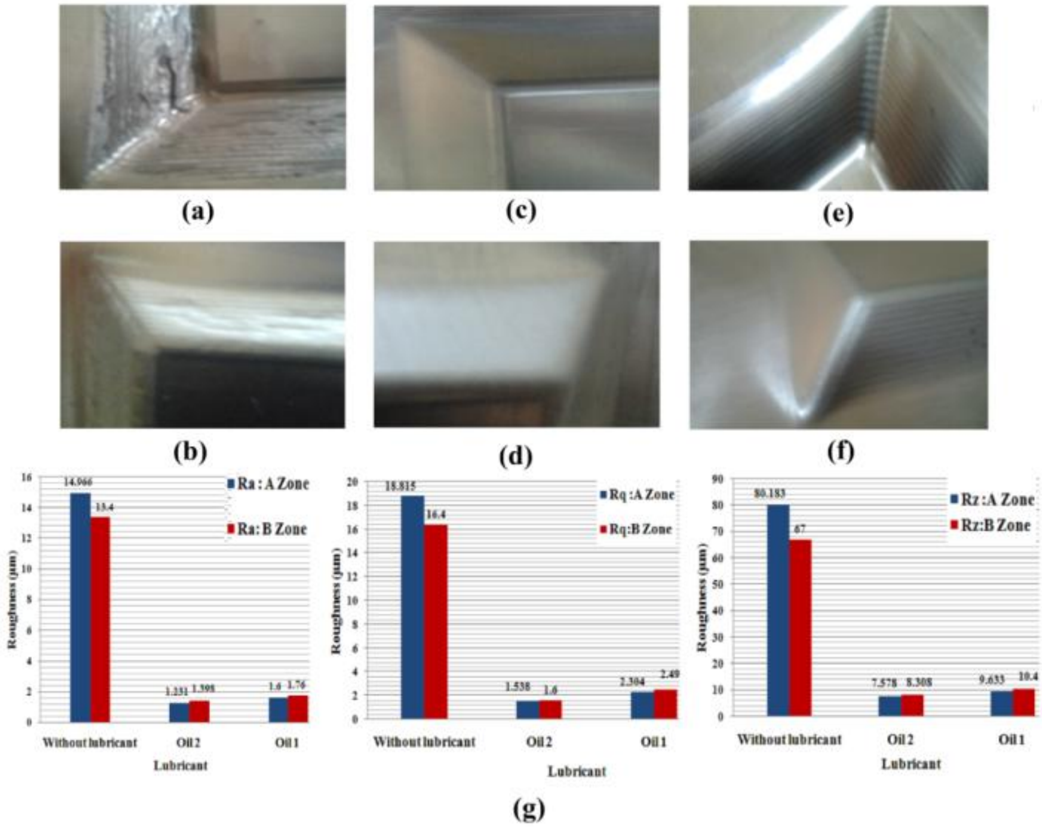

Fig.10.Surface finish of the parts produced by lubrication tests (a, b) internal and external surface (without lubrication) ;(c,d) internal and external surface (oil 2); (e,f) internal and external surface (oil 1); (e) roughness parameters (Ra,Rq, and Rz) of internal formed surface.

Hussain et al. [10] confirm that a lubricant should be closely selected as to resist to localized deformation and not squeeze out from the contact area. They also emphasize that an appropriate selection of the tool material and lubricant should be done to avoid excessive tool tip wear and sheet peeling off.

In the present work, the tool tip surface still shines after forming operation as indicated in Fig.1. Moreover, micrographic observations show that this one is not scratched. This good wear resistance of tool can be explained by its great shear strength [10]. Control of the tool geometry is carried out and this one remains unaffected. This is likely due to the high level of Z160 steel hardness (75 HRA) and its high-temperature strength. These findings are confirmed by the tests since the lubricated forming operations are conducted using oil 1 with the same lubrication method (Table 1).To ascertain the lubricant effect on surface finish, Oil 2 with characteristics illustrated by Table 2 is applied using the same lubrication method described previously.

Clear observation from Fig.10(c-f) indicates a better internal and external surface quality is obtained compared to the one obtained with oil 1.Moreover, the average roughness value is reduced with about 25%. This reduction is may be due to the greater viscosity of oil 2 (Table 2). Indeed, the more the oil is viscous, the more it is adherent and stuck at the mating surface [10], which makes difficult to squeeze out nanoparticles from the contact zone when contact pressure increases. Accordingly, the surface roughness decreases due to decrease of heating in accordance with the mechanism described previously. Otherwise, walls near the edges are less roughened with lubrication (Fig.10 (g)) (See section 3.2.1). The roughness values of the formed areas obtained using lubrication are also in the range that qualifies conventional forming processes (ASME B46.1 (2002) standard).Therefore, a choice between the two lubricants can be done to obtain better surface finish and reduce as much as possible the production cost.

4 CONCLUSIONS

In this work, it was shown that an aluminium Alloy (AA-3003-H12) pyramidal part can be successfully formed by SPIF process while satisfying reasonably good surface finish and acceptable structural integrity if the tool, the lubricant, lubrication method, and process parameter values are properly selected. The effect of process variables on the final shape geometric profile, thickness distribution, and surface finish is also studied, showing the possibility to optimize the part quality, its processing time and its production cost by an accurate control of the process parameters. Within the ranges of parameters values considered: advancing speed (50–500 mm/min), vertical step size (0.5-2 mm), tool rotational speed (1256-6283 rpm), tool diameter (10-15 mm), distance of the forming area from edges (10-75 mm), the experimental results show that:

- To form the Al-3003-H12 sheet by SPIF process, a polished tool (Z160) with the hardness of 75 HRA is found to be suitable when a proper lubrication method and lubricant are used.

- Coating the sheet blank with a sufficiently thick film of pure mineral lubricant (Shell Tellus oil 32 or Shell Dromus B), in combination with the proposed tool, is appropriate to obtain reasonably good surface finish and acceptable structural integrity.
- The proposed tool resists to wear and deformation during the forming process when the previous lubricants and lubrication method are adopted.
- Forming without lubrication does not work; the surface finish and the structural integrity of the part are dramatically affected.
- Thickness distribution and geometric profiles of the formed part do not change with process parameters variation.
- The distance of the forming area from edges affects significantly the geometric precision; this one is better when edges are near the forming area.
- Distance from edges influences the roughness but not significantly.
- The surface roughness increases with increase in vertical step and tool rotational speed, but decreases with increase in tool diameter.
- The increase of feed rate leads to an increase then a decrease of internal surface roughness.

References

[1] I. Cerro, E. Maidagan, J. Arana *et al.*, "Theoretical and experimental analysis of the dieless incremental sheet forming process," *Journal of Materials Processing Technology,* vol. 177, no. 1, pp. 404-408, 2006.

[2] "Aluminum and Aluminum Alloys," Ohio: ASM International, 1993.

[3] H. Khalatbari, A. Iqbal, X. Shi *et al.*, "High-Speed Incremental Forming Process: A Trade-Off Between Formability and Time Efficiency," *Materials and Manufacturing Processes,* vol. 30, no. 11, pp. 1354-1363, 2015.

[4] J. Jeswiet, F. Micari, G. Hirt *et al.*, "Asymmetric single point incremental forming of sheet metal," *CIRP Annals-Manufacturing Technology,* vol. 54, no. 2, pp. 88-114, 2005.

[5] F. C. Minutolo, M. Durante, A. Formisano *et al.*, "Evaluation of the maximum slope angle of simple geometries carried out by incremental forming process," *Journal of Materials Processing Technology,* vol. 194, no. 1, pp. 145-150, 2007.

[6] S. Matsubara, "Incremental backward bulge forming of a sheet metal with a hemispherical head tool-a study of a numerical control forming system II," *Journal of Japan Society for Technology of Plasticity,* vol. 35, pp. 1311-1311, 1994.

[7] Y. Kim, and J. Park, "Effect of process parameters on formability in incremental forming of sheet metal," *Journal of materials processing technology,* vol. 130, pp. 42-46, 2002.

[8] W. Wilson, "Friction and lubrication in bulk metal-forming processes," *Journal of Applied Metalworking,* vol. 1, no. 1, pp. 7-19, 1978.

[9] S. B. Echrif, and M. Hrairi, "Significant parameters for the surface roughness in incremental forming process," *Materials and Manufacturing Processes,* vol. 29, no. 6, pp. 697-703, 2014.

[10] G. Hussain, L. Gao, N. Hayat *et al.*, "Tool and lubrication for negative incremental forming of a commercially pure titanium sheet," *Journal of materials processing technology,* vol. 203, no. 1, pp. 193-201, 2008.

[11] Y. Li, Z. Liu, W. Daniel *et al.*, "Simulation and experimental observations of effect of different contact interfaces on the incremental sheet forming process," *Materials and Manufacturing Processes,* vol. 29, no. 2, pp. 121-128, 2014.

[12] W. K. Sarraji, J. Hussain, and W.-X. Ren, "Experimental investigations on forming time in negative incremental sheet metal forming process," *Materials and Manufacturing Processes,* vol. 27, no. 5, pp. 499-506, 2012.

[13] M. Dittrich, T. Gutowski, J. Cao *et al.*, "Exergy analysis of incremental sheet forming," *Production Engineering,* vol. 6, no. 2, pp. 169-177, 2012.

[14] M. Durante, A. Formisano, A. Langella *et al.*, "The influence of tool rotation on an incremental forming process," *Journal of Materials Processing Technology,* vol. 209, no. 9, pp. 4621-4626, 2009.

[15] T. Husmann, and C. S. Magnus, "Thermography in incremental forming processes at elevated temperatures," *Measurement,* vol. 77, pp. 16-28, 2016.

[16] P. Martins, L. Kwiatkowski, V. Franzen *et al.*, "Single point incremental forming of polymers," *CIRP Annals-Manufacturing Technology,* vol. 58, no. 1, pp. 229-232, 2009.

[17] A. Bhattacharya, K. Maneesh, N. V. Reddy *et al.*, "Formability and surface finish studies in single point incremental forming," *Journal of Manufacturing Science and Engineering,* vol. 133, no. 6, pp. 061020, 2011.

[18] M. Durante, A. Formisano, and A. Langella, "Comparison between analytical and experimental roughness values of components created by incremental forming," *Journal of Materials Processing Technology,* vol. 210, no. 14, pp. 1934-1941, 2010.

[19] P. Jiabao, C. Yanhai, and Y. Jinyong, "Effect of heat treatment on the lubricating properties of lithium lubricating grease," *RSC Advances,* vol. 5, no. 72, pp. 58686-58693, 2015.

[20] M. Kalin, J. Kogovšek, and M. Remškar, "Mechanisms and improvements in the friction and wear behavior using MoS 2 nanotubes as potential oil additives," *Wear,* vol. 280, pp. 36-45, 2012.

[21] G. Hussain, L. Gao, and N. Hayat, "Forming parameters and forming defects in incremental forming of an aluminum sheet: correlation, empirical modeling, and optimization: part A," *Materials and Manufacturing Processes,* vol. 26, no. 12, pp. 1546-1553, 2011.