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Lubricants and Affecting Parameters on Hardness in SPIF of AA1100 Aluminium

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***Abstract* – The local plastic deformation of a sheet, using a unique tool by different controlled path strategies with the absence of punch and die is called Single Point Incremental Forming (SPIF). It is an environmental friendly sheet forming process compared to stamping, where the manufacturing and disposal of dies are creating a huge environmental footprint. In SPIF, the forming tools are mainly kind of a metal spike with a spherical or flat end on top of it, where the diameter of the tool tip is 10 mm in average. In this study, the effects of different parameters of SPIF on the hardness of aluminium alloy sheet 1100 have been carried out experimentally and studied. The analysis of the test results has shown that hardness remarkably increases by increasing the tool speed. Furthermore, the increase in the feed rate leads to an increase in hardness. Besides, the use of various greases with not-environmental coolant oil effects presented that hardness increases using coolant oil and decreases using grease when applying the same feeds.**

Keywords – SPIF, Single Point, Incremental Forming, Sheet Forming, Hardness.

I. INTRODUCTION

Incremental sheet forming (ISF) is an active process of non-mass production regarding the cost due to the absence of punch and die. Thus it is essential to form a product using ISF with high geometry accuracy. There is governmental, academically, and in business interest about new emerging manufacturing technologies, such as ISF impact the environment. In particular, how and how much it saves energy [1]. M. A. Dittrich et al. in [2] compared two exergy analyses of ISF with traditional forming and hydroforming, and the environmental impact of these forming techniques in point of the supply chain. Consequently, they resulted from this that ISF is significantly lower harmful to the environment for non-mass production and prototypes. G. Ingarao et al. in [3] developed sustainability guidelines about advantages and disadvantageous of SPIF based on the required energy to deform the sheet and material savings in each process. They proved that SPIF allows material saving, this in the perspective of emission CO_2 due to produce the raw materials and impact of recycling possibility. It is crucial to study the mechanical properties and effective parameters before and after the forming to make this process a significant industrial application. W. C. Emmens et al. in [4] highlighted the enormous advantages of SPIF, especially the flexibility of the process, which makes it comfortable to use for more applications in industries and processes. W. C. Emmens et al. in [4] and Y. Li et al. in [5] indicated that ISF has many advantages; thus, it will be considered an asset for industrial companies in the future. One of ISF's benefits, besides increased formability, is the need for low forces because of the forming separation into several small stages. ISF is not very useful for mass production; instead, it is helpful for custom production, i.e., prototypes or one-of-a-kind production. Sherwan M. Najm and Imre Paniti in [6] observed that the flat tool showed better results than the hemispherical tool in various terms of SPIF, applying the process on Aluminium Alloy Foils. The best geometric accuracy was obtained by the smallest corner radius of the flat tool because of the decrease in spring-back. ISF as a Service was introduced by Imre Paniti in [7], who distinguished 1st order and 2nd order bottleneck parameters. He described the main capabilities of an Incremental Sheet Forming Service Provider in Cloud Manufacturing. L. Fratini et al. in [8] found a relationship between material formability and mechanical properties. It has been shown that the coefficient of hardening and normal anisotropy makes the most considerable effect on the traditional Forming Limit Diagram (FLD). Z. Liu et al. in [9] claimed that formability increases by increasing the step size in the case of a spiral path strategy. Also, the maximum vertical force increases by increasing the step size, and linearly increases by increasing the sheet thickness. Y. Li et al. in [10] found the mechanical properties and the thinning rate were affected by three parameters of ISF. It has been shown that increasing the tool diameter, considerable improves the micro-hardness of the product surface. The increment of the tool diameter and the decrement of the step size will finally increase the tensile strength rate. They claimed that contrary to step size sheet thickness significantly affects the yield strength L. Manco et al. in [11] proved that the tool trajectory could be considered as an essential parameter to optimize the process design by comparing the smallest thickness of the sheet due to varying of the tool path with the predicted thickness using sine-law.

The normal condition of hardness behaviour in SPIF is that the formed part achieves higher hardness than the unformed sheet. Q. M. D. Al-Attaby et al. in [12] showed that the tool path affects the hardness and microstructure of the formed sheet by using different path strategies and different forming angles. In all cases, the hardness was increased depending on the forming angle.

In this paper, SPIF parameters were studied by applying the process on the AA1100 Aluminium sheet. The observed parameter was the hardness of the formed sheet by the effects of the following process parameters: feed rate with grease and coolant oil, spindle speed, and rotation direction tool diameter, and different types of greases, in fact that the aspect of affecting lubricant on the ISF process has not been optimized yet, as shown in [2]. X. Song et al. in [13] found three different regions (bending/stretching, shear, and stretch/shear) based on various mechanisms of deformation. Thus in this study, hardness was measured in three different positions on the inside wall of the formed cone, and measured values were compared to the initial hardness of the sheet.

II. MATERIALS PROPERTIES

In all experiments, aluminium alloy sheet with an initial hardness 42.87 HV was used. The mechanical properties and chemical composition of the sheet material are shown in Table 1 and in Table 2, respectively. The test results of the aluminium sheet are compared with the nominal in the ASM Hand-Book V.2 [14]. The initial thickness of the sheet is 0.6 mm, with an original surface roughness of 0.29µm.

Table 1 Mechanical Properties of the sheet material

	Ultimate stresses [MPa]	Yield Strength [MPa]	Elongation [%]
Actual	110	95	20
Nominal	110	103	25

Table 2: Chemical Composition of the sheet material

Element	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Pb	B	Sn	V	Al
Actual [%]	0.110	0.482	0.004	0.005	0.001	0.0005	0.004	0.021	0.021	0.0005	0.003	0.001	0.014	99.30
Nominal [%]	0.5	0.5	0.2	0.04	0.01	Other 0.15 max								98.6-99.9

III. EXPERIMENTS

In the first step, a matrix of 3 factors which has equal levels (feed rate, spindle speed, and tool diameter) have been applied. The best values of feed rate, spindle speed, and tool diameter were chosen depending on the best geometry accuracy and maximum depth. In the second step, a matrix of 2 factors of different levels has been applied to study the coolant type and rotation direction.

Boxford 300VMCi milling machine with 0.01 mm resolution was used in this study. The ISO format using G and M codes were used to program a cone shape with a large and small diameter of 80 mm and 10 mm, respectively. The cone part was deformed by an inward spiral path strategy suggested by Skjødt et al. [15] to overcome reaching maximum axial load at each layer (step down) and prevent the appearance of a line on the inner side of the formed part. Wall angle with 45°, a context contour of 0.5 mm for the step size fz, and inward stepped fx have been applied, as shown in Fig. 1.

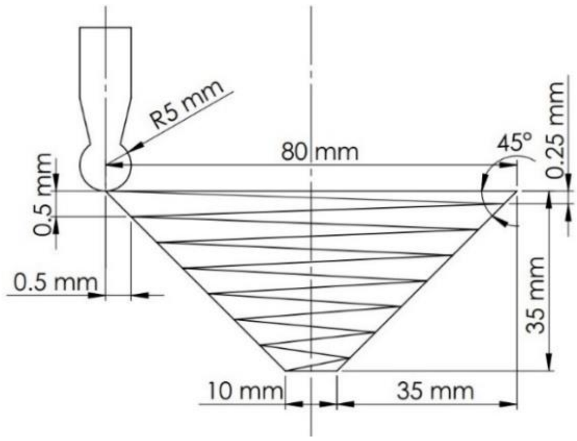


Fig. 1. Geometry of the experimental product

A forming tool with different diameters (4, 6, 8 and 10 mm) was used in the experiment. The tools are made from carbon steel with a hardness of 30 HRC and 100 mm in total length. Plain carbon steel were used as clamping rig with a straightforward fixture system to secure the set-up on the table of the CNC machine as shown in Fig. 6.

Fig. 2. Fixture and rig on the CNC machine table

A Digital Vickers Micro Hardness tester was used to measure the hardness of the formed sheet. Three products were experimentally formed for each set to study the forming parameters. For the mentioned test, hardness in each part was measured at three points. The formed part was cut to the desired shape in the proper size to prepare the test samples. The appropriate piece of the section was mounted by a mounting press device and polished by a Metaserv type 200/RP device before measuring the hardness.

There is no internationally accepted term for the definition of environmentally acceptable lubricants (EALs), and they still lack standardization. American Society for Testing and Materials (ASTM) committees used "environmentally acceptable" as a term for defining EALs [16]. However, there is an encouraging trend towards using them. Here, different coolant types were used to carry out the experiment (four different grease types and one coolant oil). Table 3 lists the grease properties. In the case of Coolant Oil, the Acidity PH is 7, the Kinematic Viscosity is 1.086 m^2/s, and the Boiling Point is 95 °C.

Table 3. Grease Properties

Grease Type	Average dropping point [°C]	Flash point [°C]
LS2 EP	90	180
Kaucuklu	88	172
Zinol	88	170
Dallas	58	60

Lubricants cannot be used in some forming processes where high loads are applied, so S. Syahrullail et al. in [17] suggested using a proper additive to solve this problem. Consequently, the difference between using coolant oil and grease is that the second one makes a mixture from itself and the small disintegrating particles (debris) from the formed sheet or, in rare cases, from the tool. Due to heat generation, sometimes the debris repeatedly sticks to the sheet surface or passes between the tool and the formed sheet. J. Diabb et al. in [18] observed the aluminium flakes in the used lubricant caused by wear adhesion on alloy sheets of SPIF components. In the case of coolant oil, which flows continuously on the sheet, the debris can be washed away from the forming zone. However, by using grease, a smoother surface can be produced compared to the variant where coolant oil was used due to the flattening and roughening effect by the debris, as stated in [19]. On the other hand, the coolant oil is continuously flowing during the forming process, whereas the grease will be put on the sheet surface just one time at the beginning of the process. In other words, coolant oil has higher exergy than the grease as a consequence of difference using amount, which means more environmental burdens.

Four different tool rotation speeds in each direction, clockwise and anticlockwise, were used to study hardness behaviour. Also, four different feed rates were implemented to investigate the effects of changing the feed rate on the forming sheet hardness. Table 4 shows the values of the speed and the feed rates applied in the current experiments.

Table 4. Feed and Speed values

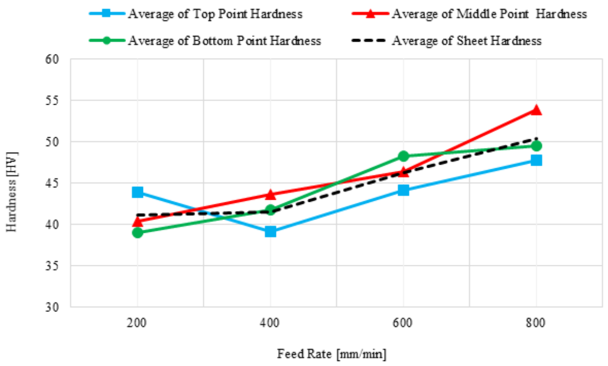
Feed rate [mm/min]	Speed Clockwise [rpm]	Speed Anticlockwise [rpm]
200	500	500
400	1000	1000
600	1500	1500
800	2000	2000

For hardness measurement, 100 N was applied with the Vickers diamond pyramid indenter for 15 seconds on the formed part. After adjusting the rhomb corner that was triggered by the indenter, the results were recorded automatically on a digital screen.

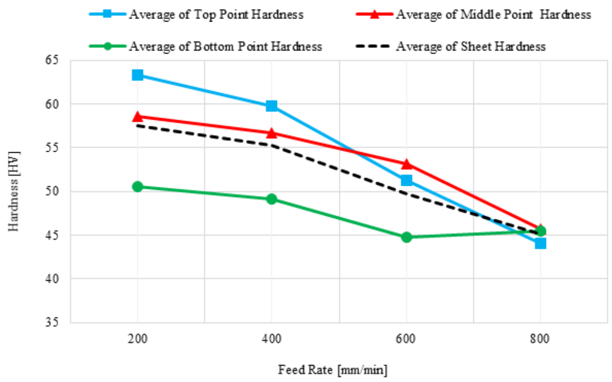
IV. RESULTS AND DISCUSSIONS

A. Feed Rate

Four different feed rates were used with different lubricants (Oil and Grease). Other experimental parameters were fixed as the clockwise speed was 2000 rpm, and the tool diameter was 10 mm using coolant oil. Fig. 3 shows hardness according to the feed rate. Changing the lubricant type gives an inverse value of hardness. It grows by increasing the feed rate using coolant oil (Fig. 3 (a)) and falls using grease (Fig. 3 (b)).



(a)



(b)

Fig. 3. Effect of the different feed rate on the microhardness formed sheet
(a) by using a coolant oil, (b) by using grease

The increase of the feed rate led to an increase of hardness, and this is inversely proportional to the formability. The increase in the feed rate causes a decrease in formability, as mentioned in [20]. Hardness decreasing is due to changes in the surface asperities because of shooting and breaking the peak of them by generated debris. Sticking the debris to the tool and cultivating the sheet surface creates new grooves, in addition to crashing the sharp peak of the asperities. Finally, by continuously cultivating and crashing, the contact area between the tool and formed sheet will increase.

J. Hol et al. in [21] mentioned that under normal force, the sheet surface asperities are in a plastic condition, and only a little stress in the underlying bulk material has a further effect on them. They claim that this stress is perpendicular to the normal force and generates more plastic deformation of asperities. Finally, because of the enormous strain of the underlying material, hence leading to an increased contact area which is recognized as a decrease in effective hardness.

B. Tool Speed

Fig. 4 shows that the increase in the tool speed led to the increase of hardness. High speed leads the existing particles to impact the surface of the sheet faster than in the case of low speeds, and this resulted in the hardening of the surface. Due to stretching with longitudinal deformation, the sheet material seems to be under cold working conditions. Cold working creates a different type of crystal deformation, such as compressing, twisting, and bending, which comparatively ensues a uniform plain crystalline. New imperfections created by these movements result in more resistance and finally, increases hardness.

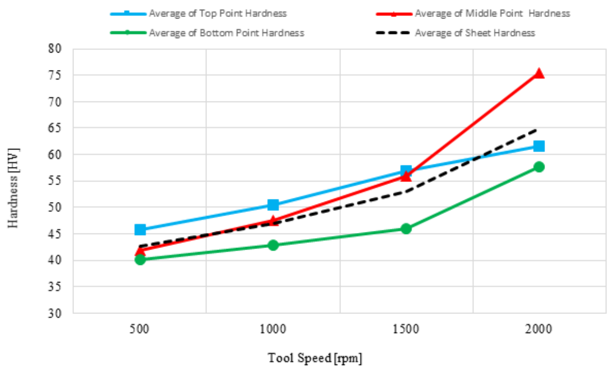


Fig. 4. The effect of different tool speed on the microhardness formed sheet (Feed rate: 600 mm/min, Tool diameter: 10 mm, Coolant oil)

C. Tool Diameter

The effects of the tool diameter on hardness are presented in Fig. 5. Decreasing outcomes are due to the increase in tool diameter. T. McAnulty et al. in [22] found different behaviours in the effects of changing the tool diameter on formability. A. Asgari et al. in [23] noticed that a tool diameter of 3 mm gives higher hardness to aluminium alloy 1100-O sheet than 5 mm and 10 mm tool diameter. By decreasing the tool diameter from 10 mm to 3 mm, the ultimate tensile stress and the yield stress decreased by 7% and 24%, respectively. Furthermore, the grain size decreased too by reducing the tool diameter. P. Shrivastava and P. Tandon in [24] referred to various parameters of the sheet before producing it and studied their effect on the ISF process and the final properties of products. They claimed that the forces needed to form the sheet in ISF are affected by the grain size. Increased grain size leads to a decrease in forming force, yield stress, and hardness. In their experiments, a tool diameter of 4 mm showed higher hardness than the other diameters at all the points. The tool diameters of 10 mm and 8 mm gave lower hardness values than the tool diameters of 6 mm and 4 mm. Besides, the reasons before the larger tools which passed through the formed sheet more times than the smaller tools made the material of the formed part softer (causing more heating with more friction).

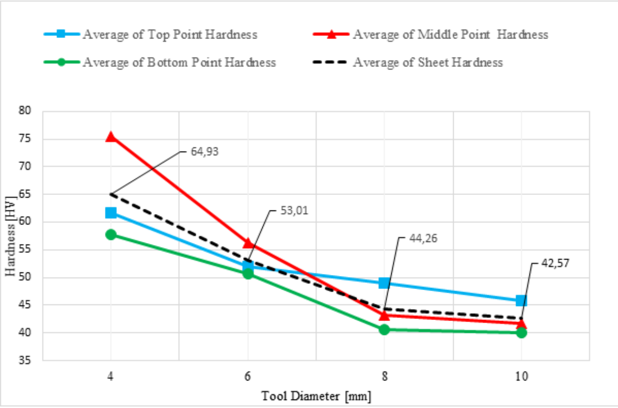


Fig. 5. The effect of different tool diameter on the microhardness of the formed sheet (Feed rate: 600 mm/min, Tool speed: 2000 rpm, Coolant oil)

D. Different Greases

Fig. 6 shows the hardness results affected by different greases. The grease with the highest dropping point gave the lowest hardness and vice versa. The grease type with the name "Dallas" provided the highest hardness (with the lowest dropping point) by entering between the tool and the formed sheet and cooling the localized forming zone faster. Regarding the different grease properties, it is shown that the grease with a higher flash point gave a more stable hardness value. Although, it can be noted that the hardness at different points of the same sheet is more homogeneous by using grease than using coolant oil.

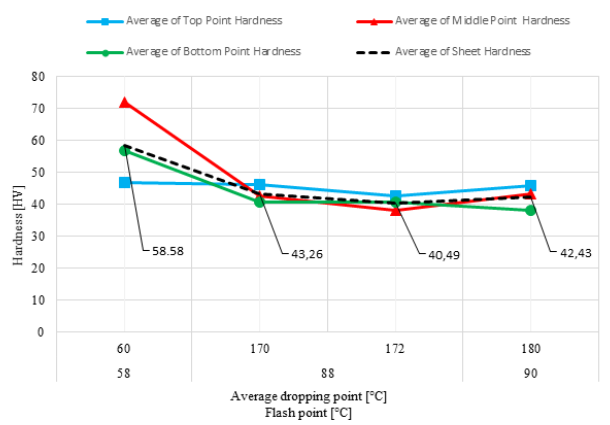


Fig. 6. Properties effect of different grease type on the microhardness of the formed sheet (Feed rate: 600 mm/min, Tool speed: 2000 rpm, Tool diameter: 10 mm)

V. CONCLUSIONS AND OUTLOOK

In this study, fourteen SPIF experiments with incremental selection and factor reduction have been applied to investigate the effect of feed rate, spindle speed, tool diameter, coolant type, and rotation direction. Considering the limits of the allowed combinations of possible measurement points and that only some partial DoE plans could be realised, it has to be taken into account that the paper gives conclusions only in these partial directions but not as comprehensive process analysis. From this work, the following findings can be concluded:

- Increasing the feed rate increases hardness using coolant oil. The hardness decreases by using grease (by filling the grooves between asperities with the debris carried by the grease).
- The hardness of the component increases by increasing the tool speed.
- Increasing in tool diameter resulted in decreasing the hardness of the components.
- Grease properties definitely affect the hardness value. Using grease instead of coolant oil conducts a homogenous value of hardness at different points of the same formed sheet.

So, to summarize the first three findings we can state that to increase the hardness of a SPIF component made of AA1100 Aluminium, high feed rates and tool speed have to be applied with coolant oil, instead of grease by using tools smaller than 8 mm in diameter.

The authors are planning to investigate different tool materials that could affect hardness. Furthermore, experiments with various materials of the sheet, but under the same conditions are being considered.

VI. ACKNOWLEDGMENTS

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