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Surface and Friction Characterisation of Rotational Vibration-assisted Incremental Sheet Forming

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Abstract. As a die-less manufacturing technique, the incremental sheet forming (ISF) is a flexible and potentially cost-effective process for producing small-batch or customised sheet products with complex geometries. However, some important limitations of the ISF have prevented this flexible sheet forming process to be utilised for industrial applications. These limitations include low surface finishing, unacceptable springback and inability to process hard-to-form materials at room temperature. To overcome these limitations, a new rotational vibration-assisted ISF (RV-ISF) by creating a novel rosette tool concept has been developed in the University of Sheffield. In this study, RV-ISF tests using new tools are conducted to create straight grooves and rectangular pyramids to evaluate surface quality of the parts formed by the RV-ISF process. Friction conditions between the RV-ISF tool and the deforming sheet, as well as part surface roughness and surface texture are measured and evaluated. The results provide an insight into the effect of new tool design and key parameters on the interfacial friction condition and surface quality of the new RV-ISF process.

Keywords: Incremental sheet forming, interfacial friction, surface quality.

1 Introduction

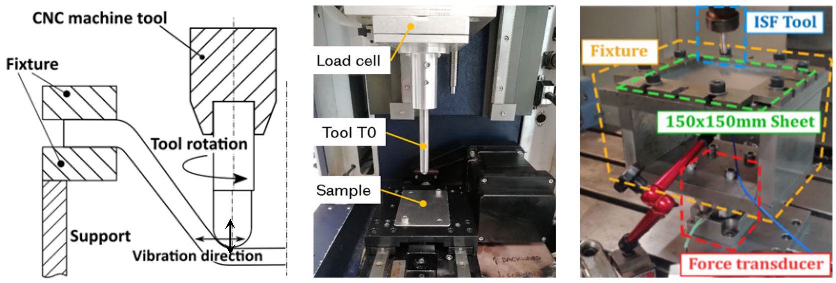
ISF is a relatively new sheet metal forming process that has gained significant attention in recent decades due to its ability to produce complex geometries using a simple forming tool. The conventional ISF process includes single point incremental forming (SPIF). SPIF can be performed on a 3-axes CNC machine to drive a hemispherical headed tool to deform a sheet blank along a predefined toolpath to create a desired geometry. Friction-stir incremental sheet forming (FS-ISF) has emerged as a promising variant of ISF to process hard-to-form materials, where a rotating forming tool creates frictional heating to soften the material locally to achieve greater plastic deformation without sheet fracture. The high adaptability of ISF allows the process to be extensively studied in the past decades where the formability, geometrical accuracy and surface quality, as well as the effect of the process parameters on these key characteristics are evaluated.

One of the key challenges in ISF is to achieve good surface quality, which is influenced by various process parameters such as tool path strategy, feed rate, and lubrication, as well as tool rotational speed in FS-ISF. Over the years, a number of studies have been reported to investigate the factors affecting the surface quality in ISF. The impact of the tool rotation on the surface quality in FS-ISF has been a focus of investigation, in addition to study the formability improvement. Bhattacharya et al. [1] experimentally studied the effects of forming angle, tool diameter, step depth of the tool path on the formability and surface finishing in the SPIF process. The results suggested that increasing wall angle and tool diameter had a negative effect for achieving a good surface finishing. It was observed that a larger step depth of the tool path firstly led to poor surface finishing but when reaching a certain forming angle, the surface finishing improved. Ambrogio et al. [2] studied the effect of local heating due to tool rotation on the surface quality of AA2024-T3, AZ31B-O and Ti6Al4V. It was found that reducing the forming angle of the formed geometry led to a lower surface roughness. Hagan and Jeswiet [3] conducted experiments by SPIF using AA3003 and found that the surface roughness was influenced by step depth of the tool path and tool rotational speed. It was observed that the surface roughness was increased with the increase of step depth. The tests also obtained an optimal rotational speed for reducing the surface roughness. Hamilton and Jeswiet [4] investigated the effect of tool feed rate and rotational speed on surface roughness, thickness distribution and microstructure as well as the surface texture of "orange peel" in the SPIF. Chang and Chen [5] proposed an analytical model for predicting surface roughness by considering material properties, sheet thickness, forming wall angle, tool radius and step depth. The analytical modelling results combined with experimental results highlighted the dominating effects of the tool contact traces and friction on the final surface quality of ISF parts. The optimisation of lubrication, tool rotational speed and feed rate was necessary to improve the final surface finish.

The improvement to material deformation by employing additional tool vibration in ISF was reported. Vahdati et al. [6] and Amini et al. [7] applied an ultrasonic device to create vibration on the tool tip in ISF groove tests. The forming force reduction during the ultrasonic vibration assisted ISF (US-ISF) was observed leading to a significant formability enhancement. Similar results were also reported in detailed experimental investigations by Li et al. [8] and Zhang et al. [9], which suggested the application of localised vibration could be a solution to achieve the surface quality improvement in ISF. However, the requirement of the additional equipment makes the US-ISF being less flexible and less economically efficient. Lu et al. [10] employed an elliptical headed tool to enable tool rotation-induced vibration in incremental sheet forming (V-ISF), generating relatively low vibration frequencies but higher vibration amplitudes than that in the UA-ISF. Microstructure refinement was observed and laminated ultrafine grains and higher micro hardness were obtained at the inner side of the formed hyperbolic cone by the V-ISF process.

A new forming method named as Rotational-Vibration assisted Incremental Sheet Forming (RV-ISF) is proposed for the first time by developing a novel concept of rosette tools in the University of Sheffield. As shown in Fig.1(a), the RV-ISF process creates rotational vibration via employing a novel tool design without the need of using any additional device. Combining the tool induced sheet vibration and frictional heating due to tool rotation, the RV-ISF can improve the material formability of hard-to-form materials. The new rosette tool design can generate localised vibration by discontinuous contacts with the formed sheet wall through designed offsets or rosette grooves distributed on the tool head. The new tools have the easy-to-deploy feature using a CNC machine for performing the RV-ISF process.

This paper presents a study of the RV-ISF experimental tests in forming straight groove and rectangular pyramid geometries to calibrate interfacial friction and benchmark surface quality of the RV-ISF parts when using different tools. The effects of tool rotational speed, feed rate, and lubrication by using three different tools on the surface roughness are evaluated. The characteristics of the RV-ISF process and effect of the tool design on friction and surface quality are discussed.



(a) (b) (c)

Fig.1. Illustration of (a) rotational-vibration assisted incremental sheet forming (RV-ISF), (b) reference friction testing by UMT, and (c) RV-ISF experiment by CNC machine.

2 Experimental Testing Methods

The coefficient of friction between tool and sheet material is measured in the reference tests on a Bruker's Universal Mechanical Tester (UMT) machine by following the standard procedure, as shown in Fig.1(b). A constant load of 100~250N and tool speed of 500 and 1000 mm/min are used in the reference tests.

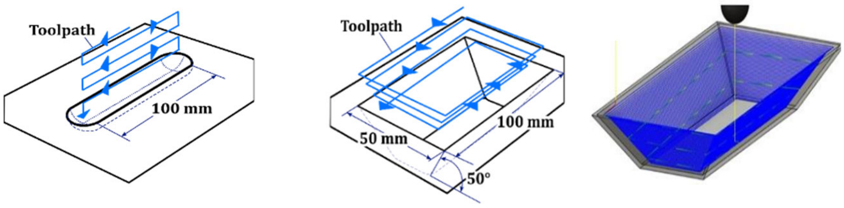
The RV-ISF tests are conducted on a 3-axis CNC milling machine using a sheet-clamping fixture as shown Fig.1(c). Aluminium alloy AA5052 sheets with size of 150×150mm and 1mm thickness are used to produce straight groove and rectangular pyramid geometries for benchmarking. The two geometries produced in the tests and their respective toolpaths are shown in Figs.2(a) and 2(b). A force transducer is placed under the fixture to record the tool forming forces. The forming forces measured are used to estimate the friction indicator of the flat contact surface of the formed straight groove and of the sidewall of the formed rectangular pyramid. After the tests, Alicona SL Infinite Focus-SL is used to obtain high-resolution optical measurements of surface roughness and surface texture of the formed pyramid.

Three different tools are used in the RV-ISF experimental tests, as shown in Fig.3. The hemispherical headed tool (T0) is used as a reference for FS-ISF tests. The T2 tool of an elliptical cross-section with 2-offsets and the T4 rosette tool with four grooves on the hemispherical tool head are tested to evaluate the effect of tool vibration on friction indicator and surface roughness.

For the FS-ISF and RV-ISF tests, the friction indicator μ^* is calculated according to the measured horizontal and vertical forming forces, given by Lu et al. [11]:

$$\mu^* = \frac{|F_{Horizontal}|}{|F_{Vertical}|} = \frac{friction + forming\ load}{|F_Z|} \tag{1}$$

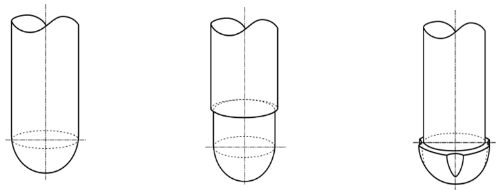
The friction indicator in the RV-ISF process is determined when the forming tool passes the longer edge of the straight groove or the rectangular pyramid, where the forces measured are stable and at the minimum. This is because at this location, the stable material deformation is achieved and the contact condition resembles the actual forming condition in the RV-ISF process.



(a) Straight groove (b) Rectangular pyramid

Fig.2. RV-ISF tests: (a) straight groove/ toolpath, (b) rectangular pyramid/toolpath.

- Tool head dia. for all tools =10mm
- T2: elliptical tool major/minor dia. = 10mm / 8mm
- T4: rosette tool groove = 6.5mm



(a) T0 (b) T2 (c) T4

Fig.3. Tools used in FS-ISF and RV-ISF tests: (a) hemispherical headed tool (T0), (b) elliptical headed tool of 2-offsets (T2), (c) 4-groove rosette tool (T4).

3 Results and Discussions

Fig. 4 shows coefficient of friction (COF) using T0 tool measured by the UMT on the surface of sheet AA5052, under different conditions of the contact load and tool feed speed on dry or machine oil lubricated sheet surface. Fig.4(a) shows that the COF in dry tests increases with contact load but the tool feed speed does not show a significant effect on COF. Oil tests reduce the COF by 19% when compared with dry tests, under contact load of 100 N and tool feed speed of 500 mm/min.

The RV-ISF experimental tests are organised into two groups according to the two different geometries formed. The parameters of straight groove tests are listed in Table 1 and the tests for the rectangular pyramid are outlined in Table 2. In the RV-ISF straight groove tests, two different values of step depth in 0.3 and 0.5 mm, two different tool feed rates of 500 and 1000 mm/min, are tested under different tool rotational speeds of 0, 2000, 3000, 4000 rpm using oil and grease lubricants.

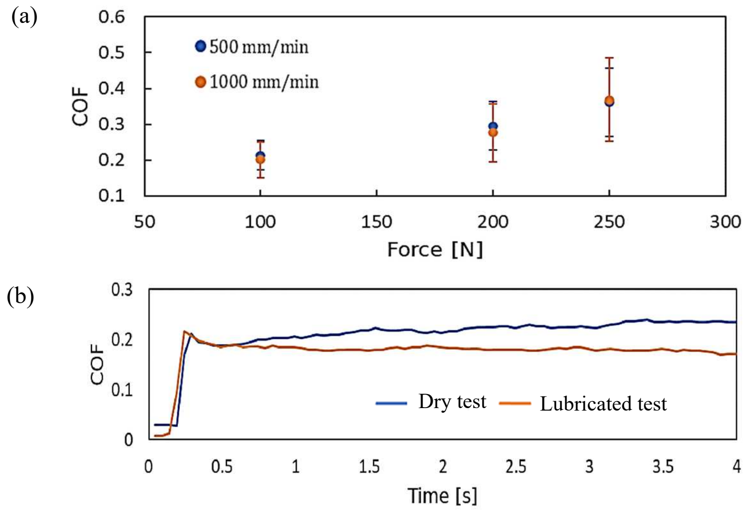


Fig.4. Coefficient of friction by UMT: (a) dry; (b) dry and lubricated (100N, 500mm/min)

Table 1. RV-ISF test parameters in forming straight groove geometry by CNC.

No.	Rotation (rpm)	Lubrication	Step depth (mm)	Tool	Feed rate (mm/min)	Friction indicator using stabilised forces
1.1	0	Oil	0.3	T0	1000	0.151
1.2	0	Oil	0.5	T0	1000	0.155
1.3	0	Metal cutting compound	0.5	T0	1000	0.155
1.4	2000	Oil	0.5	T0	500	0.087
1.5	4000	Oil	0.5	T0	500	0.085
1.6	2000	Oil	0.5	T2	500	0.262
1.7	4000	Oil	0.5	T2	500	0.325
1.8	2000	Oil	0.5	T4	500	0.117
1.9	3000	Oil	0.5	T4	500	0.131

Fig. 5(a) and Table 1 show the friction indicator obtained from the RV-ISF tests by CNC in forming the straight groove. The results suggest that different tool designs play a significant role on contact friction. For the T0 tool, the friction indicator is reduced with the increase of tool rotational speed, with the lowest friction measured using 2000 and 4000 rpm. It is clear that the increasing tool rotational speed helps the feed of oil into the contact surface between the tool and sheet. However, for the T2 and T4 tools, the friction indicator shows an increasing trend with the increase of tool rotational speed, in which T2 tool shows extremely higher values of friction indicator and increasing rate than that of T4 tool.

This highlights a key characteristic of the new RV-ISF tool design that the rotational speed determines the tool contact condition during forming. Under a high rotational speed using T2 and T4, the increasing contact time between the tool and sheet results in an increase of friction indicator. However, such an effect on the surface quality should be further evaluated and this will be discussed later in this section. Comparing Fig. 4(b) and Fig. 5(b), it is clear that the COF measured by the UMT test using the T0 tool is similar to the variation trend and level of the friction indicator obtained from the RV-ISF test using T0 without tool rotation.

Table 2 summarised the RV-ISF tests using CNC in forming the rectangular pyramid geometry. These tests provide an assessment of the actual friction condition in the RV-ISF process and its effect on surface roughness of the formed parts.

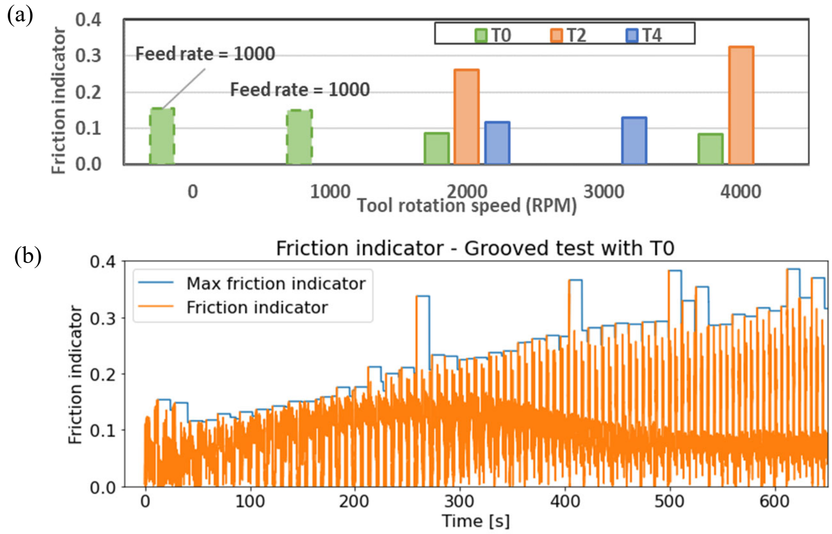


Fig.5. Friction indicator from RV-ISF groove tests by CNC: (a) effect of tool design and tool rotational speed, (b) variation during RV-ISF test using T0 without tool rotation.

Table 2. RV-ISF test parameters in forming pyramid (step depth=0.3mm) by CNC

No.	Rotation (rpm)	Lubricant	Tool	Feed rate (mm/min)	Ra (µm)	Last 3mm Ra (µm)	Sa (µm)	Friction indicator using stabilised forces
2.1	2000	Oil	T0	1000	2.37	2.13	4.33	0.125
2.2	3000	Oil	T0	1000	2.87	2.57	4.88	-
2.3	2000	Oil	T2	1000	2.49	3.67	4.75	0.184
2.4	3000	Oil	T2	1000	3.07	4.51	6.54	-
2.5	2000	Oil	T4	1000	3.00	2.04	5.09	0.11
2.6	3000	Oil	T4	1000	2.74	1.88	4.88	0.124
2.7	4000	Oil	T4	1000	2.59	1.68	5.25	-
2.8	3000	Oil	T4	500	2.76	2.39	5.13	0.151

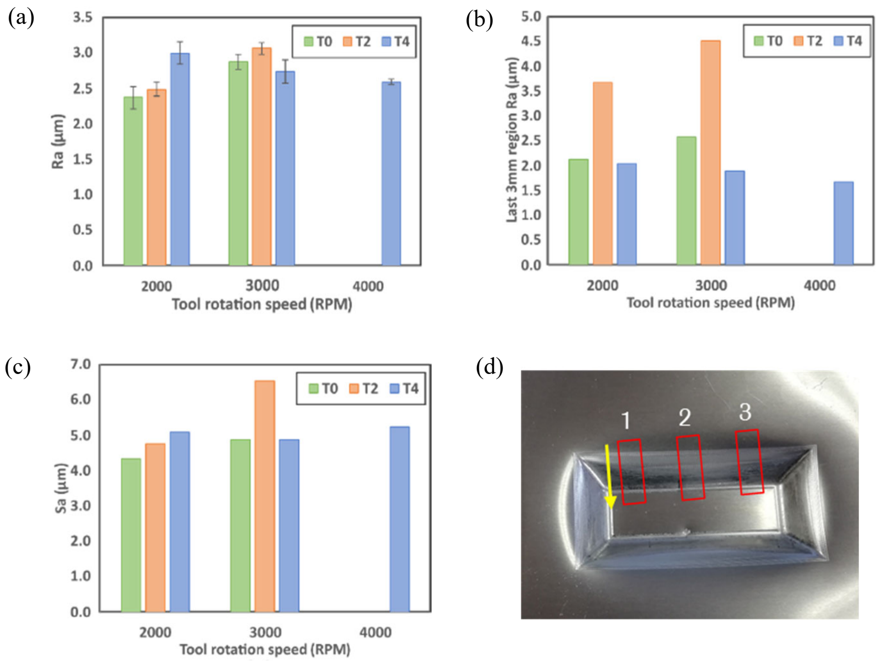


Fig.6. Surface roughness measurement of the RV-ISF rectangular pyramid samples by T0, T2 and T4: (a) full-length surface roughness Ra; (b) local surface roughness Ra of last 3mm of the pyramid bottom; (c) full-length surface texture roughness Sa; and (d) three measurement regions and the full-length measurement indicated by the arrow.

Fig.6 compares the surface roughness measurement results of the sidewall of the formed rectangular pyramid in the regions shown in Fig.6(d), produced using different tool rotational speeds from 2000 to 4000 rpm under tool feed rate of 1000 mm/min. The results obtained using T0 and T2 tools agree with the measurement data from the groove tests, which also agree with published studies [3, 10, and 12], that increasing the tool rotational speed leads to poor surface quality. However, this trend is reversed in the RV-ISF tests using the T4 tool. The surface roughness of the samples obtained by the RV-ISF using the T4 tool is reduced from 3.00 µm at 2000 rpm to 2.74 µm at 3000 rpm, which is slightly smaller than 2.87 µm from the sample produced by the FS-ISF using the T0 tool at 3000 rpm. The Ra value of the surface roughness is further reduced to 2.59 µm at 4000 rpm by using the T4 tool, the lowest surface roughness measured from all rectangular pyramid tests.

There are two conclusions that can be made based on these results. Firstly, the tool design is the most critical factor in the RV-ISF process that determines how the tool interacts with the sheet surface thus determining the friction behavior and surface quality. The T4 tool shows an improvement brought by the localised vibration from the tool design and rotation in the RV-ISF, similar observations reported in the previous UA-ISF studies [8]. However the RV-ISF is more flexible and a low-cost process variant in comparison with the US-ISF. Secondly, the feed rate is a negligible factor because the surface roughness from tests 2.6 and 2.8 are almost identical while two different feed rates are used. Fig.6(b) shows the local mean surface roughness Ra of the sidewall of the formed rectangular pyramid in the region at 3 mm distance to the bottom of the pyramid, where the tool head is in full contact with the sidewall thus the vibration effect is better established. It can be seen in Fig.6(b) that the variation trend of local surface roughness with increasing tool rotation speed is the same as the variation of the full-length surface roughness in Fig.6(a). The surface quality is better at greater forming depth of the pyramid bottom by the T0 and T4 tools, while it becomes worse in the same region by the T2 tool. The surface quality by the T4 tool is better than that by the T0 tool in this region of measurement, as shown in Fig.6(b), due to the established full contact between the sheet and tool, enhancing the effect of tool vibration.

Fig.7 presents the surface texture roughness Sa of the full length of the sidewall of the rectangular pyramid using T0, T2 and T4, comparing surface quality of FS-ISF and RV-ISF samples. The values of surface texture roughness by the T4 tool are greater than that produced by T0 and T2. However, a closer observation of four graphs of the surface texture roughness provide further information of surface finish. As can be seen, a unique fish-scale texture can be observed on the surface in the sidewall region of the pyramid, especially in the region formed at the beginning of the process. This is resulted from the combined tool motion due to the localised and periodical tool vibration and tool feeding, which leaves layered tool contact traces.

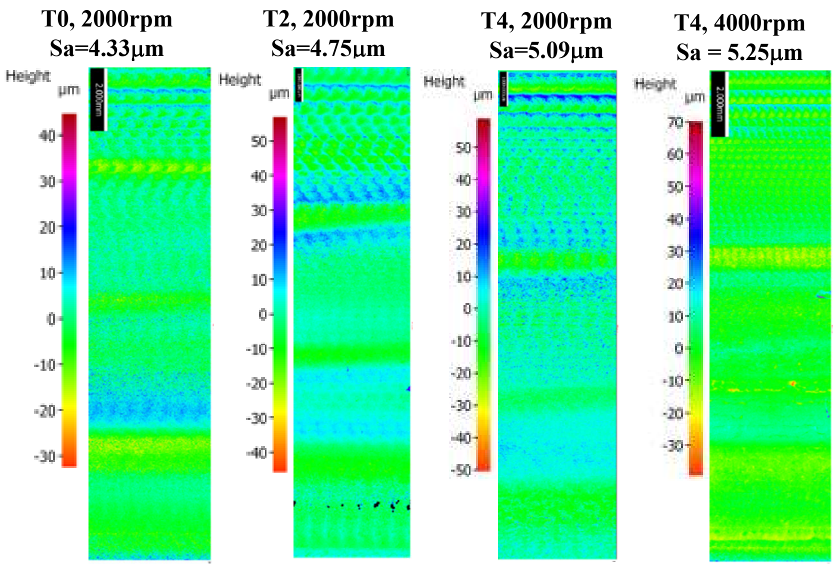


Fig. 7. Surface texture of sidewall on full-length of pyramid by FS-ISF and RV-ISF tests.

As shown in Fig.7, by comparing the surface texture produced by T4 tool at 2000 and 4000 rpm, it can be seen that the RV-ISF process diminishes the fish-scale texture resulting in an improved surface quality. This is because an increased tool rotational speed leads to a higher frequency of tool-sheet contact impact and strengthened vibration effect. However, it is noticeable that the same phenomenon is not observed by using the T2 tool, which shows a negative effect on surface quality by increasing tool rotational speed when using a tool with higher vibration amplitude, such as T2. The T4 tool shows the ability to maintain uniform distributions of surface texture roughness thus an improved quality against the increase of tool rotational speed. This means that a better surface finish can be achieved by using the rosette tool that can also improve the formability when requiring higher tool rotational speeds. The optimisation to the RV-ISF process parameters should be considered together with the tool design to achieve a balance between the benefits of vibration to improve formability and surface quality.

From the forming mechanism perspective, the RV-ISF process combines the benefits of tool rotational to create frictional heating in the FS-ISF and the vibration effect in the UA-ISF, thereby exhibiting characteristics of both processes. The surface roughness is directly affected by the mixed deformation mode at localised contact between the tool and sheet surface. Therefore, adjusting the proportion of contact area and vibration energy through the optimised RV-ISF tool design can further enhance surface quality.

5 Conclusions

This study investigates the RV-ISF as a new ISF process that focuses on enhancing the formability and surface finish for hard-to-form materials. The RV-ISF employs a novel design of the rosette tool that can generate both frictional heating and localised vibration during the forming process. Based on the experimental results, the following conclusions may be drawn:

- The unique tool design plays a decisive role on the frictional condition at the tool-sheet interface thus surface quality of the formed parts in the RV-ISF;
- The friction indicator using T2 and T4 tools in the RV-ISF increases with the tool rotational speed, whereas in the FS-ISF using T0 tool it shows an opposite trend;
- A higher tool rotational speed leads to an increased surface contact duration between the tool and sheet in the RV-ISF process, resulting in an increased frictional heating and friction indicator;
- T4 tool reduces the formation of fish-scale surface texture thus improves the surface quality due to its low frequency and low amplitude vibration in the RV-ISF process;
- Tool design is the most critical factor in the RV-ISF that determines the friction behaviour and surface quality. The optimisation of tool design and process parameters in the RV-ISF process can lead to the realisation of its full potential to improve both material formability and surface quality.

Acknowledgments

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