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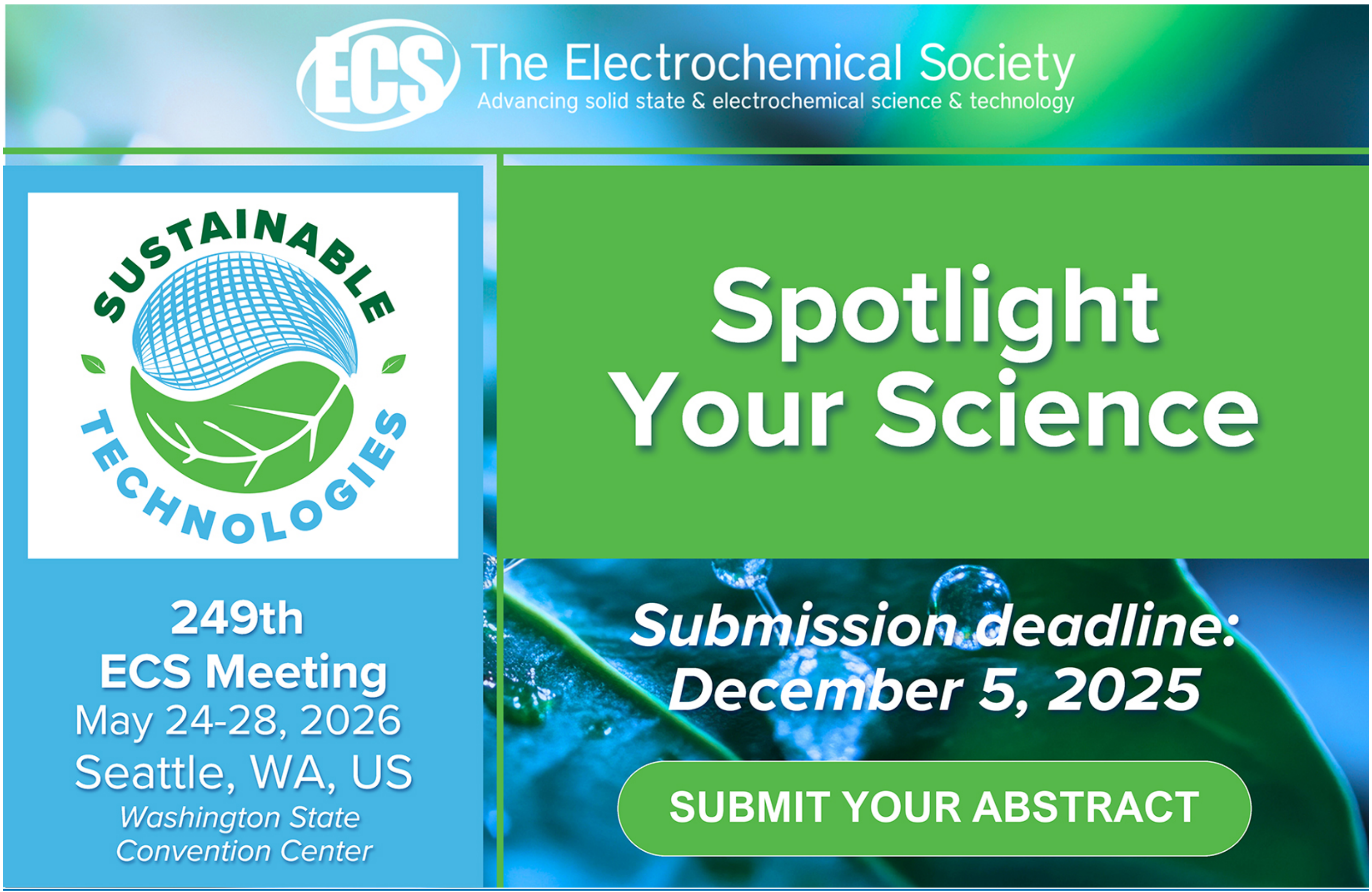

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The Effects of Rosette Tool Geometry on the Rotational Vibration-Assisted Incremental Sheet Forming Process

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Abstract. Rotational Vibration-assisted Incremental Sheet Forming (RV-ISF) has emerged as a flexible process for manufacturing complex geometries with significant potential for wider applications. An experimental study was performed on a square pyramid geometry to investigate the effect of tool geometry and process parameters such as rotational speed and step size on the forming process of AA5251 H22 alloy sheets. The process was monitored using a suite of sensors to measure vibrations, force, and temperature, as well as machine tool data. Data from the eddy current sensor show that increasing rotational speed generally reduces vibration amplitude for RV-ISF tools by 27%, indicating more frequent but shorter-duration tool-sheet contact events at higher speeds, while finer step sizes increase vibration activity by 8%. Force and thermal measurements were also obtained, highlighting the influence of rotational speed, step size, and tool design on the thermo-mechanical response, with RV-ISF tools reducing frictional heating more effectively than conventional ISF tools by 22%. The results explain how tool design and process optimization can enhance vibrational and thermal softening in the incremental sheet forming process. This study contributes to the understanding of RV-ISF tool geometries by comprehensively monitoring the process with sensors and machine data and provides insights for improving part quality in incremental sheet metal forming.

1. Introduction

Incremental Sheet Forming (ISF) has gained significant attention due to its adaptability in producing customized and small-batch sheet metal components. Emmens et al. (2010) [1] provided an overview of the historical development of ISF, highlighting its progression in recent decades. The ISF process encompasses several variants, including single-point incremental forming (SPIF), two-point incremental forming (TPIF), and double-sided incremental forming (DSIF). Duflou et al. (2018) [2] presented a detailed analysis of SPIF, discussing its current advancements and potential applications across diverse domains. Despite its numerous advantages, challenges remain. Studies by Attanasio et al. (2008) [3] and Hirt et al. (2021) [4] revealed that industrial application of ISF is hindered by issues such as low geometric accuracy, poor surface finish, and sheet thinning that can lead to fractures. The progress also struggles to process difficult-to-form materials, especially those with low ductility at room temperature.

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Techniques such as friction stir incremental forming (Otsu, (2010) [5] and Wang et al. (2020) [6]) and ultrasonic-assisted incremental forming (Long et al. (2018) [7] and Amini et al. (2017) [8]) demonstrate how process enhancements lead to positive effects on the sheet forming process. Zhan et al. (2022) [9] introduced a two-stage friction stir-assisted method, while Lu et al. (2017) [10] explored vibration-induced softening using an elliptical tool. These studies underscore the importance of process optimisation in improving ISF performance.

Among the different variations of Incremental Sheet Forming (ISF), advanced techniques such as Rotational Vibration-Assisted Incremental Sheet Forming (RV-ISF) have been introduced by H. Long et al. (2024) [11] to overcome challenges related to surface quality, geometric accuracy, and forming limits. This method incorporates an innovative rosette tool design that integrates vibrational and rotational dynamics to improve tool-sheet interactions, reduce forming forces, and enhance material formability. This study further contributes to the investigation of the RV-ISF by comprehensively monitoring the process with sensors and machine data offering insights into the incremental sheet metal forming process. This comprehensive experimental work investigates the influence of tool geometry and process parameters such as rotational speed and step size on the vibrational and thermomechanical characteristics during the forming process.

2. Experimental Approach

2.1 Experimental setup

The RV-ISF trials were conducted using a C52 Hermle Machine tool, a high-precision 5-axis CNC milling machine, to investigate the effect of rotational vibrations on incremental sheet forming. The experimental setup (Figure 1(a)) consisted of an experimental rig, a robust clamping system to secure the sheet metal, a Kistler plate dynamometer (Type 9255C) for force measurements, a FLIR A700 thermal camera for temperature monitoring, and an eddy current sensor for capturing displacement data (Figure 1(b)). The sensors were strategically placed, and the eddy current sensor specifically positioned by the sidewall of the geometry to capture localized displacement data. This sensor was connected to a National Instruments (NI) Data Acquisition (DAQ) device, which was linked to the data acquisition PC via USB. Machine controller data was gathered using Transmission Control Protocol/Internet Protocol (MQTT) over an Ethernet connection to track spindle position and power. High-speed real-time data acquisition was facilitated by MATLAB-based in-house data acquisition software. The sensor data was recorded at a sampling rate of 50,000 Hz, while the machine controller data was collected at 333 Hz.

(a) **(b)**

Figure 1(a-b). Schematic of RV-ISF setup

Three distinct tool variants (Figure 2(a-c)), designed by the University of Sheffield [11] and manufactured by Technicut Limited (tooling solutions company), were utilized to study the influence of tool geometry on vibration characteristics: Tool 1: (T0) 0-Groove Tool – A conventional forming tool without grooves; Tool 2: (T3) 3-Groove Tool and Tool 3: (T4) 4-Groove Tool – Designed to introduce controlled vibrational effects.

(a) 0 Groove tool (T0) **(b) 3 Groove Tool (T3)** **(c) 4 Groove Tool (T4)**

Figure 2(a-c). RV-ISF tools

2.2 Experimental design

The experimental study was performed on a square pyramid geometry (Figure 3) with the dimensions of 84mm*84mm*30mm. The effects of tool geometries and process parameters such as rotational speed (RPM 2000 & RPM 3000) and step size (0.2mm & 0.3mm) were studied to understand the impact on the forming process of aluminium alloy AA5251-H22 with 1mm thickness.

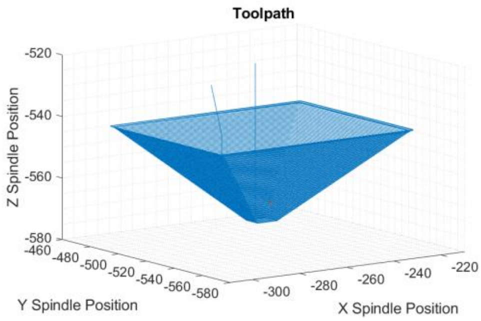


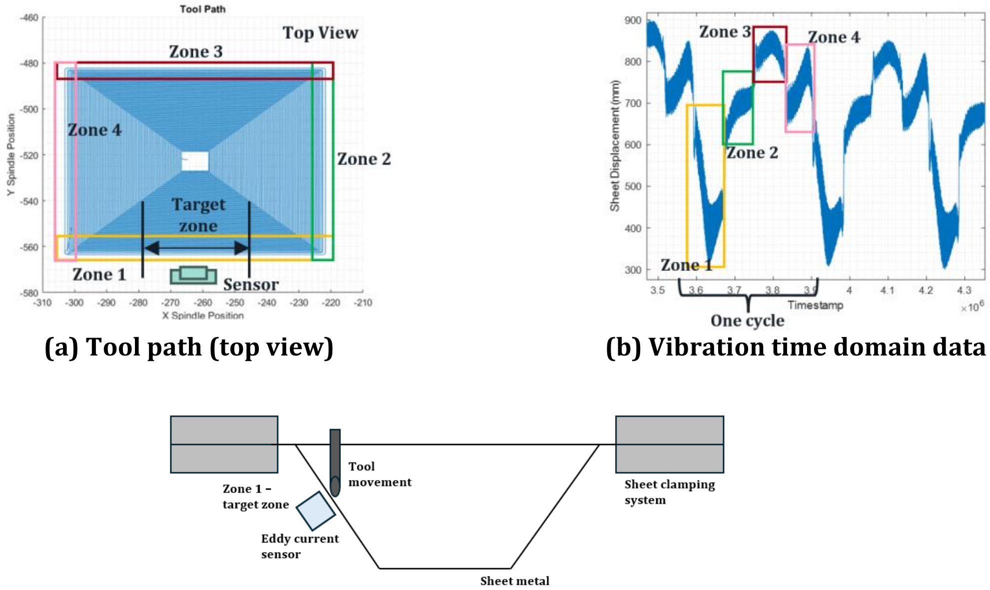
Figure 3. 84 mm x 84mm square pyramid geometry with helical toolpath

A helical toolpath, as seen in Figure 3, was generated for incremental sheet forming due to several key advantages [12]. The continuous nature of the helical path ensures uniform material deformation, leading to smoother and more gradual deformation while reducing localized thinning and strain concentrations. It also results in better surface quality, as continuous tool movement minimizes surface defects and tool marks, producing a more uniform and smoother finish. Additionally, the helical toolpath enhances formability by facilitating the forming of complex geometries and reducing abrupt shape transitions, thereby improving overall part accuracy and integrity.

3. Data capture and processing methodology

3.1 Vibration data processing approach

Figure 4(a-c) illustrates the variations in the displacement measured from the eddy current sensor relative to the tool's position (zone 1 – zone 4). Each segment is highlighted with a specific colour box (Figure 4(a)), aiding in the visualization of the displacement data (Figure 4(b)). The displacement data in zone 1 (yellow box) is particularly important because the tool is closest to the sensor position (Figure 4(c)). In contrast, the displacement data recorded in zones 2 to 4 are not considered in this study, as they do not accurately represent vibration induced by the tool movement.



(a) Tool path (top view) **(b) Vibration time domain data**

(c) Visulization of tool at the point nearest to the sensor

Figure 4(a-c). Correlation between tool path and vibration data

The process to convert the raw displacement signal into the relevant outputs of frequency and amplitudes involves several steps: first, obtaining zone 1 data where the tool is closest to the sensor (Figure 4(c)); then narrowing down the zone 1 data to focus on the start and end points near the sensor, referred to as the 'Target Zone'; followed by centralization of the 'Target Zone' region, which enhances frequency analysis by eliminating unwanted low-frequency components that may distort the spectrum, improving accuracy and facilitating easier comparison between different trial data by aligning vibration patterns across multiple trials; and finally, applying Fast Fourier Transformation (FFT) to extract vibration frequency and amplitude. The spindle position data recorded from the C52 Hermle machine enabled precise tracking of the RVISF tool throughout the forming process, allowing for accurate identification of the exact location of zone 1 data when the tool was closest to the eddy current sensor.

3.2 Forming force data processing approach

Vertical forming forces were recorded using a Kistler 9255C plate dynamometer. To ensure accurate measurement of forces generated solely by the forming operation, the clamping system and the rig were designed to match the dimensions of the dynamometer's surface. This setup effectively eliminates the influence of bending moment forces, ensuring precise force acquisition during the forming process. The vertical forming force is in the Z direction (the axis perpendicular to the plane of the sheet metal).

3.3 Forming temperature data processing approach

Temperature monitoring during the incremental sheet forming process was conducted using the FLIR A700 Professional Science Kit Thermal Camera. The camera was strategically positioned inside the machine tool, away from the sheet forming area as depicted in Figure 1(a). The setup allowed for accurate capture of the temperature on the sheet metal surface. An emissivity test was carried out and the value of emissivity was set to 0.8 during the measurements.

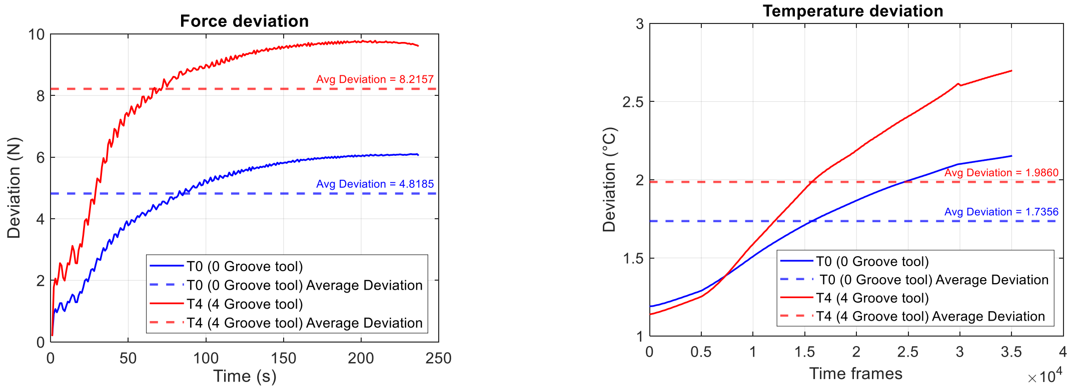
4. Data analysis

4.1 Experimental repeatability tests

A repeatability test was performed to evaluate the consistency and reliability of the measurement system under the same condition. This assessment is essential for ensuring measurement accuracy, identifying variability, and optimizing process control. High repeatability signifies minimal random errors, leading to reliable data for decision-making. The test was carried out three times each with the T0 (0 Groove tool) and T4 (4 Groove tool) at 2000 RPM with a step size of 0.3 mm. Table 1 represents the vibration amplitudes for the repeatability tests. The eddy current sensor exhibited good repeatability, with a 18.7% and 4.8% variation respectively in incremental sheet forming vibration measurements.

Table 1. Vibration amplitude repeatability test data

Trial	Tool Design	Rotational Speed (RPM)	Step Size (mm)	Measured Amplitude (µm)	Mean Amplitude (µm)	Standard Deviation (µm)	Repeatability (%)
1	T0	2000	0.3	3.40	2.8	0.52	18.7
2	T0	2000	0.3	2.42			
3	T0	2000	0.3	2.59			
4	T4	2000	0.3	19.37	20.27	0.98	4.8
5	T4	2000	0.3	21.31			
6	T4	2000	0.3	20.13			



(a) Forming force deviation **(b) Forming temperature deviation**

Figure 5(a-b). Forming force and temperature repeatability plots

Figure 5(a-b) illustrates the deviation in force and temperature measurements across the three trials. Each point on the graph represents the difference between the maximum and minimum values, indicating how much variability exists within each set of measurements. The average deviation is shown as a horizontal dashed line, providing a benchmark for the overall consistency. This plot helps in visualizing the extent of variability in readings. The results show a good consistency in the forming force having an average deviation of 4.8N for the T0 (0 Groove tool) and 8.2N T4 (4 Groove tool). In addition, the forming temperature has an average deviation of 1.7°C for the T0 (0 Groove tool) and 1.9°C T4 (4 Groove tool).

4.2 Vibration analysis

Table 2 represents the measured frequencies and amplitudes for the RV-ISF trials carried out. The reference frequency refers to the frequency of contact between a rotating tool and the sheet metal and it is calculated as follows: $\frac{Number\ of\ grooves \times Rotational\ speed}{60}$

Table 2. Vibration data frequency and amplitude

Trial No	Tool Design	Rotational Speed (RPM)	Step Size (mm)	Reference Frequency (Hz)	Measured Frequency (Hz)	Measured Amplitude (µm)
1	T3	2000	0.3	100	97.50	34.15
2	T3	3000	0.3	150	147.49	20.41
3	T4	2000	0.3	133.33	129.99	22.38
4	T4	3000	0.3	200	194.99	19.34
5	T0	2000	0.3	0	10	2.95
6	T0	3000	0.3	0	50	4.05
7	T3	2000	0.2	100	97.5	30.8
8	T4	2000	0.2	133.33	129.99	19.39
9	T0	2000	0.2	0	32.49	2.12

Figure 6 represents the relationship between vibration amplitude with rotational speed and step size. It is important to note that theoretically, there is no tool-sheet vibration when the T0 (0 Groove tool) tool is used, and the recorded amplitude is from the tool eccentricity and the frequency is just: $\boldsymbol{\frac{Rotational\ speed}{60}}$

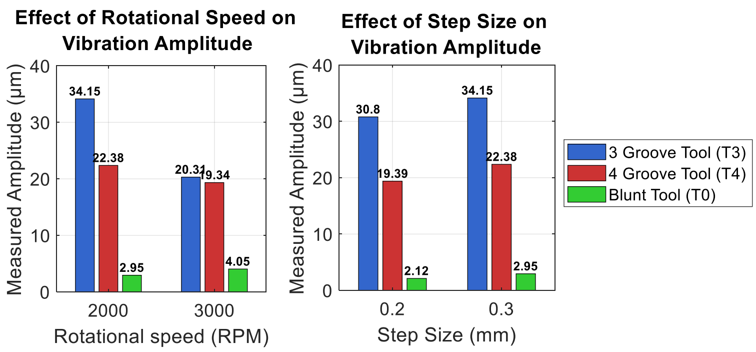
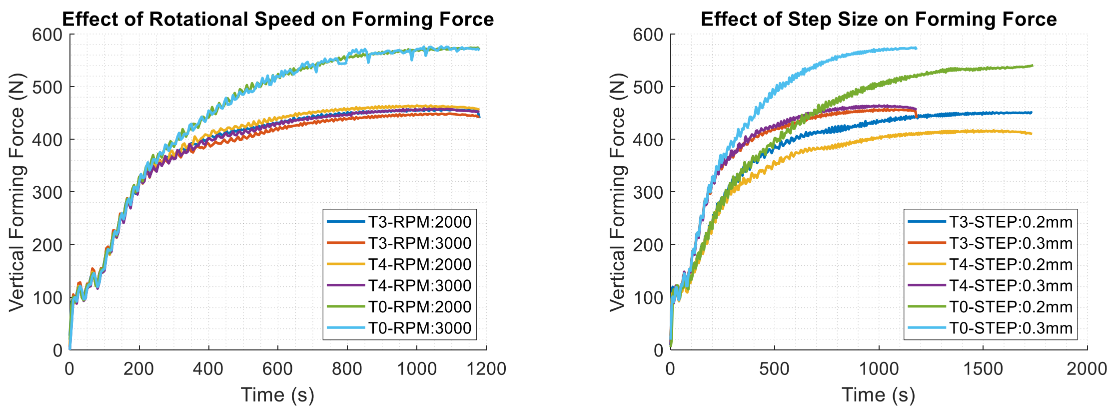


Figure 6. Influence of rotational speed and step size on vibration amplitude

The results show the following points: In terms of the influence of rotational speed on the amplitude, for T3 (3 Groove tool), increasing rotational speed from 2000 to 3000 led to a 40% reduction in vibration amplitude, suggesting that higher rotation speed reduces effective contact discontinuities. This is because grooved tool dynamics introduce periodic interruptions in contact with the sheet metal. Increasing rotational speed results in more rotations per unit time, causing the grooves to pass over the contact area more frequently thereby reducing contact frequency as the sheet metal only experiences contact during the solid (non-grooved) portion of the tool, effectively decreasing the number of discrete contacts per second. T4 (4 Groove tool) showed a smaller reduction of 14% in amplitude, indicating a different mechanical response due to groove configurations. Regarding the influence of step size on amplitude, for T3 (3 Groove tool), the amplitude increased by 11%, showing moderate sensitivity to step size, while T4 (4 Groove tool) showed a 5% increase, indicating a relatively minor dependency. T0 (0 Groove tool), however, experienced a dramatic 39% increase, reinforcing the continuous tool-sheet interaction.

4.3 Forming force analysis

Figure 7(a-b) represents the relationship between the vertical forming force with the rotational speed and step size. As rotational speed increases from 2000 to 3000, the vertical forming force decreases, indicating that higher rotational speed reduces material resistance and lower the required force. To quantify the difference, the force profiles are compared across the entire dataset range for the three tool designs. The force signals were interpolated onto a common time vector to enable accurate point-to-point comparison. The difference between the two force profiles were calculated, and the corresponding percentage difference was determined. Finally, the average percentage decrease was computed, providing a comprehensive measure of the overall force reduction achieved by increasing the rotational speed. The forming force decreases by 2.1% for T3 (3 Groove tool), 2.6% for T4 (4 Groove tool), and 0.9% for T0 (0 Groove tool). Higher rotational speed increases frictional work and elevates the temperature at the tool-sheet interface, whereas at a lower rotational speed of 2000, the forming force remains consistently higher, suggesting that material deformation occurs under lower heat conditions with greater resistance. Thus, increasing spindle speed tends to reduce forming forces. Similarly, step size significantly affects forming force, as increasing it from 0.2 mm to 0.3 mm results in higher forces due to more material being deformed per tool pass, leading to increased resistance. The force decreases by 9.1% for T3 (3 Groove tool), 15.2% for T4 (4 Groove tool), and 15.8% for T0 (0 Groove tool) when using a smaller step size. A smaller step size allows for gradual deformation, reducing force demand and potentially enhancing surface finish. Therefore, reducing the step size helps minimize forming forces, improving formability while potentially reducing both tool and material damage. It is also observed that the T0 (0-groove tool) generates the highest vertical forming forces when compared to the grooved tools.

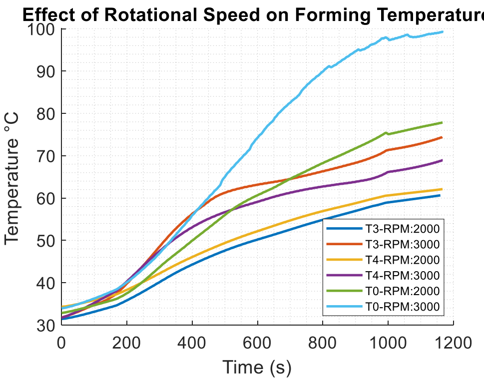


(a) Rotational speed vs vertical forming force **(b) Step size vs vertical forming force**

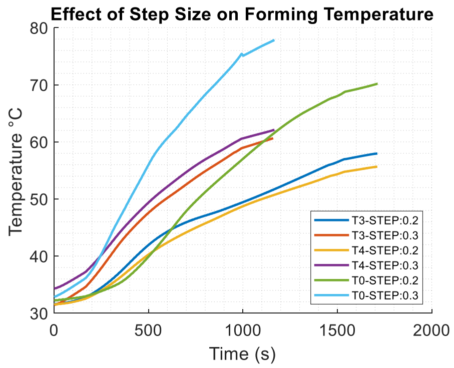
Figure 7(a-b). Influence of rotational speed and step size on vertical forming force

4.4 Forming temperature analysis

Figure 8(a-b) represents the forming temperature dependency on the rotational speed and step size. The influence of rotational speed on forming temperature shows that increasing rotational speed from 2000 to 3000 results in higher temperatures due to increased frictional work at the tool-sheet interface, a trend observed across all three tool designs. The average increase in forming temperature across the entire dataset range was calculated using the same methodology outlined in section 4.3. T3 (3 Groove tool) experienced a 16% increase, T4 (4 Groove tool) saw an 8.1% increase, and T0 (0 Groove tool) had the highest increase at 15.5%, likely due to prolonged contact time at a single location, which accumulates heat and intensifies thermal effects. In terms of step size, a finer step size of 0.2mm led to a decrease in forming temperature. The temperature decrease was 11.4% for T3 (3 Groove tool), 17.2% for T4 (4 Groove tool), and 21.2% for T0 (0 Groove tool). Grooved tools exhibit a more significant temperature rise at higher RPMs due to localized frictional effects at the tool-sheet interface, while a smaller step size reduces the number of contact points per forming cycle. However, this also induces lower strain per step, meaning more energy is required for deformation.



(a) Rotational speed vs forming temperature



(b) Step size vs forming temperature

Figure8(a-b). Influence of rotational speed and step size on forming temperature

5. Correlation between vibration amplitude, force, and temperature in RV-ISF

The thermo-mechanical response in RV-ISF results from the interaction of forming force, temperature, and vibration amplitude, which are influenced by tool geometry, spindle speed (RPM), and step size. Table 3 represents how these parameters affect process efficiency, formability, and material behaviour.

Table 3. Relation between force, temperature, and vibration amplitude

Parameter	Effect on forming force	Effect on forming temperature	Effect on vibration amplitude
Higher rotational speed	↓ Decreases (material softening)	↑ Increases (frictional heating)	↓ Decreases (for T3, T4) / ↑ Increases (for T0)
Higher Step Size	↑ Increases (more material per pass)	↑ Slightly Increases	↑ Increases, especially in T0
Grooved Tools (T3, T4)	↓ Reduces force	↑ Increases temperature but more controlled	↓ Reduces vibration
Non grooved tool (T0)	↑ Highest force	↑ Highest temperature	↑ Highest vibration amplitude

5.1 Correlation between forming force and vibration amplitude

Forming force and vibration amplitude are influenced by rotational speed, step size, and tool geometry. Higher rotational speed reduces forming force through increased frictional heating and material softening, but its effect on vibration amplitude varies with tool design. For grooved tools, increased rotational speed lowers vibration amplitude, improving stability due to more frequent tool-sheet contact. Fewer grooves have a stronger effect, while more grooves alter vibration damping. Non-grooved tools show higher vibration amplitudes with increased rotational speed, as continuous tool contact amplifies vibrations. Larger step size increases forming force and causes a moderate vibration rise in grooved tools, but a more significant increase in non-grooved tools. Grooved tools thus enhance stability by reducing both forming force and vibration, while step size influences them differently.

5.2 Correlation between forming force and temperature

Higher rotational speed reduces forming force but raises forming temperature for all tools, due to frictional heating. Non-grooved tools see the highest temperature rise from prolonged contact, while grooved tools experience more controlled increases. Larger step sizes raise forming force but only slightly increase temperature, with rotational speed being the dominant factor in temperature rise. Reducing step size lowers both force and temperature, with grooved tools helping distribute heat more evenly, preventing excessive buildup.

5.3 Correlation forming temperature and vibration amplitude

Higher temperatures generally lower forming force but don't always reduce vibration. At higher rotational speed, grooved tools show higher temperatures but lower vibrations, suggesting frictional damping stabilizes vibrations despite increased heat. Non-grooved tools exhibit both higher temperature and vibration, due to continuous contact amplifying instability. Smaller step sizes reduce temperature with minimal impact on vibration, while larger step sizes slightly increase both. Higher temperatures tend to lower forming force, but their effect on vibration depends on tool geometry and process settings.

6. Conclusions

This study confirms that rotational speed, step size, and tool geometry significantly influence the thermo-mechanical responses in RV-ISF. Increasing rotational speed stabilizes vibration amplitude for grooved tools but increases vibration for the non-grooved tool, although the non-grooved tool exhibits lower overall vibration frequencies. Higher rotational speed reduces forming force due to improved material flow, while a larger step size increases forming force due to greater material deformation per pass. Forming temperature increases with higher rotational speed due to frictional heating. The non-grooved tool experiences the highest temperature rise, while grooved tools maintain more controlled temperature increases due to their intermittent contact patterns. A smaller step size reduces forming temperature, minimizing excessive thermal buildup and enhancing formability. The relationships among forming force, temperature, and vibration amplitude highlight that tool geometry plays a crucial role in process stability. Grooved tools mitigate excessive vibrations and distribute heat more evenly, leading to lower forming forces and improved formability. Understanding these correlations enables better process optimization, enhancing tool longevity and forming efficiency in RV-ISF. Future work will focus on evaluating geometric accuracy, surface roughness, and microstructural characteristics, with expanded testing on high-strength materials and varied geometries to assess Rosette tool versatility. FFT analysis along the tool path will explore spatial vibration behaviour, while key process metrics will be compared across materials for a comprehensive performance assessment in incremental sheet forming.

7. Acknowledgement

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