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EFFECT OF THERMAL ASSISTANCE ON THE JOINING OF AL6063 DURING FLOW DRILL SCREWDRIVING

Jamie D. Skovron, Durul Ulutan, Laine Mears
Clemson University
International Center for Automotive Research
Greenville, SC, USA

Duane Detwiler, Daniel Paolini
Honda R&D Americas
Raymond, OH, USA

Boris Baeumler
DEPRAG, Inc.
Lewisville, TX, USA

Laurence Claus
EJOT® GmbH
Bad Laasphe, Germany

ABSTRACT

An increase in fuel economy standards has affected automakers' decision toward designing lightweight vehicles and therefore transitioning from steel-based bodies to ones predominantly composed of aluminum. An introduction to lightweight materials couples that of lightweight joining with a thermo-mechanical process, Flow Drill Screwdriving (FDS). This process is favored in terms of robustness, short installation time, and only requiring access to one side. The most significant challenge of this process is reducing the material sheet separation to minimize any possibility of corrosion buildup. Warm forming of aluminum has been shown to increase ductility and formability of the material and thus the process benefits from a reduced cycle time that leads to cost reduction. In this study, the effect of an auxiliary heat source on the flow of Al6063 is investigated for the FDS application. In order to accomplish this task, a conduction-heating ring is implemented into the FDS process to raise the material temperature and thus reduce the total cycle time. Different pre-process material temperatures are studied to determine the effect of material temperature on the process time, installation torque, and sheet separation. As a result, with the thermal assistance, a reduction in the process time up to 52%, the maximum installation torque by 20%, and sheet separation by 11% were attained, indicating better quality joints at a lower cost.

INTRODUCTION

Research in warm (200-350°C) forming of aluminum alloys has shown a benefit towards increasing the material formability [1, 2]. In processes that involve both thermal and mechanical aspects, researchers are motivated to introduce an external heat source to the process to increase material ductility. In a feasibility study in this direction, an increase in the maximum draw height with increasing die temperature was discovered during warm aluminum drawing [3]. The study conducted by Bolt can be related to FDS through the extrusion forming step whereby the bottom material is drawn out to increase thread engagement area. When heated to 250°C, the height of a conical stretched-drawn product increased by 65% compared to that of a similar product at 20°C. It is essential to understand and utilize the effect of these elevated temperatures on the mechanical properties of the material after the forming process.

Research in the post warm-forming mechanical properties of AA7075 [4] showed that when forming temperature is between 220°C and 260°C, the yield strength decreases by 10-14% and hardness decreases by 8-9% as compared with the as-received material. When temperatures reached 300°C, the yield strength and hardness dropped 44% and 27%, respectively. Li and Ghosh performed uniaxial [5] and biaxial [6] warm forming research on aluminum alloys. In their uniaxial tensile deformation study, they showed an increase in elongation with an increase in temperature and a decrease in elongation with an increase in strain rate. Strain rate during Li and Ghosh's study is related to the fastener force during the FDS process, whereby the engineer can control how quickly the fastener is installed into the material stackup. A lower axial force would allow greater elongation and thus a larger extrusion (drawn material from bottom sheet) for thread forming. However this would not only decrease process time but also increase forming temperature, which can lower the post-forming mechanical properties of the joint. In Li and Ghosh's biaxial tensile deformation study, they implemented a punch-die experimental setup where they discovered similar results in terms of a reduced yield strength but higher elongation percentage for high forming temperatures. The effect of warm forming on flow stress and behavior has also been studied [7,8,9,10], and the results revealed that for a constant strain rate, the flow stress decreases with an increase in temperature. High strain rate forming of aluminum alloys [11] has been researched to simulate performance during automotive frontal impact with higher flow stresses and lower fractured strain occurring with increasing strain rates.

Flow Drill Screwdriving (FDS) is a one-sided thermo-mechanical joining process classified by 6 steps (Figure 1): *heating*, *penetration*, *extrusion forming*, *thread forming*, *screwdriving*, and *final torquing*. The fastener is subjected to rotational speeds of 6000rpm on the surface of the top material (step 1: *heating*). The frictional forces generated lead to localized softening of the material which allows the fastener to penetrate the material stackup (step 2: *penetration*). Material then flows axially along the fastener, and forms an extrusion on the back side of the stackup (step 3: *extrusion forming*). Once the extrusion is formed, the fastener forms female threads on the interior of the stackup (step 4: *thread forming*). Once the threads are solidified, the male fastener threads are engaged (step 5: *screwdriving*). The rotational speed is then lowered and the fastener head is seated on the top material, and the fastener is torqued to a desired value (step 6: *final torquing*).

FDS evolved from friction drilling whereby the friction between a rotating conical tool and the workpiece softens the material and allows the tool to penetrate and form an extrusion. As the tool used during friction drilling is smooth, it does not form threads in the extrusion and thus a tap is required in addition to separate installation of a fastener. FDS combines this three step process into one.

Miller and Shih performed various studies on the friction drilling process. A study on the friction drilling of cast metals [12] showed a reduction in thrust force and torque for workpiece pre-heating temperatures ranging from 25°C to 300°C of Al380. The benefits presented by this cast metal study prompted the pre-heating of material during this current FDS study. Miller and Shih then studied the effect of friction drilling on the microstructure of steel, aluminum, and titanium [13]. The hardness values of the Al5052 increased from 0.5 (as-received) to a maximum of 2.8 on the Knoop hardness scale, however no process temperature was provided. Due to the aluminum's high thermal conductivity, the reduction of hardness is gradual over the workpiece with measurements only taken up to 800 microns from the formed hole. Further work by the same authors analyzed the experimental and numerical aspects of friction drilling [14], thermo-mechanical finite element modeling of friction drilling [15], and tool wear in friction drilling [16].

FDS carries many advantages over traditional joining methods. Self-piercing rivets do not require a pre-hole but must have access to both sides for the punch-die assembly; blind rivets can be assembled from one side but require a pre-hole; FDS combines the benefits of the two with its one-sided accessibility and absence of a pre-hole. FDS is also a robust process that utilizes the same fastener (unless combining higher strength materials such as steels and 7000 series aluminum) and equipment irrelevant of stackup material or thickness; only the process parameters are modified. Authors [17] previously studied the effect of these process parameters on joint quality where no significant difference in static strength was discovered, but variation was observed in material sheet flow and process temperature. As detailed in the 6 steps of FDS, the fastener is utilized as the tool which eliminates any consideration towards tool wear. The addition of thermal assistance to the FDS process is aimed at reducing process time, maximum installation torque, and sheet separation.

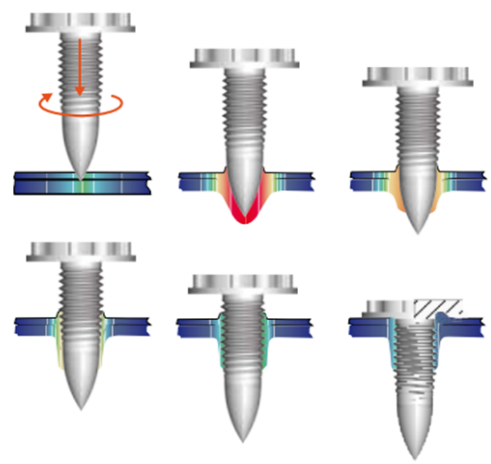

FIGURE 1: SIX STEPS OF THE FDS PROCESS

MODELING DESIGN

FDS is a thermally-driven process. The heat generated by the process is a function of rotational speed, force, and contact time between the fastener and the workpiece. The amount of axial force is inversely proportionate to the contact time (a higher axial force relates to less contact time thus less heat generation). The maximum installation torque is also driven by the temperature of the material. If the material is pre-heated, it has already experienced some thermal softening, and should require less installation torque of the fastener.

An analytical model was developed to predict the final material temperature during the FDS process. The temperature predicted through the model and actual observations are compared, Table 1. The heat generation model accounted for the heat generated by the fastener torque (Equation 2) and the amount lost through convection of a pre-heated material (Equation 3).

$$\boldsymbol{Q} = \boldsymbol{Q_{torque}} - \boldsymbol{Q_{conv}} \quad (1)$$

$$Q_{torque} = T(t)\omega(t) \quad (2)$$

Consider peak temperature occurs at center of fastener, and decays to θ_∞ at radius r_{eq}. (Figure 2).

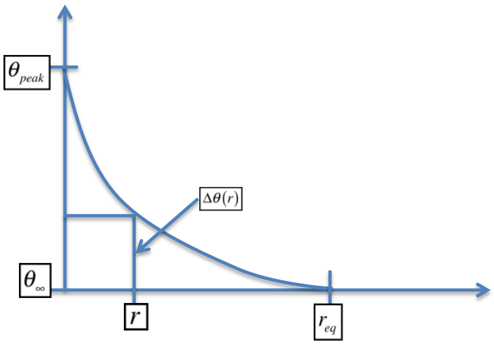

FIGURE 2: MODEL TEMP. DISTRIBUTION

Convective heat transfer rate,

$$dQ = h\Delta\theta(r)dA$$

$$\Delta\theta(r) = \theta_{peak} e^{\frac{r\ln(\theta_\infty/\theta_{peak})}{r_{eq}}}$$

$$dA = 2\pi r dr$$

$$\int_0^{Q_{conv}} dQ = 2\pi h \int_0^{r_{eq}} r\Delta\theta(r)dr$$

$$Q_{conv} = 2\pi h\theta_{peak} \int_0^{r_{eq}} r e^{\frac{r\ln(\theta_\infty/\theta_{peak})}{r_{eq}}} dr$$

$$Q_{conv} = 2\pi h\theta_{peak} \left[\frac{r_{eq}(\theta_\infty/\theta_{peak})^{\frac{r}{r_{eq}}}\left(r\ln(\theta_\infty/\theta_{peak}) - r_{eq}\right)}{\ln^2(\theta_\infty/\theta_{peak})} \right]_0^{r_{eq}}$$

$$Q_{conv} = \frac{2\pi h\theta_{peak}}{\ln^2(\theta_\infty/\theta_{peak})}\left[r_{eq}^2(\theta_\infty/\theta_{peak})\left(\ln(\theta_\infty/\theta_{peak}) - 1\right) + r_{eq}^2\right]$$

(3)

Therefore, heat rate is (Equation 4),

$$Q = T(t)\omega(t) - \frac{2\pi h\theta_{peak}}{\ln^2\left(\frac{\theta_\infty}{\theta_{peak}}\right)}\left[r_{eq}^2\left(\frac{\theta_\infty}{\theta_{peak}}\right)\left(\ln\left(\frac{\theta_\infty}{\theta_{peak}}\right) - 1\right) + r_{eq}^2\right]$$

$$H = \int_0^{t_f} Q dt = \int_0^{t_f} T(t)\omega(t)dt - 2\pi h r_{eq}^2 \int_0^{t_f} \frac{\theta_{peak}(t)}{\ln^2\left(\frac{\theta_\infty}{\theta_{peak}(t)}\right)}\left[\left(\frac{\theta_\infty}{\theta_{peak}(t)}\right)\left(\ln\left(\frac{\theta_\infty}{\theta_{peak}(t)}\right) - 1\right) + 1\right]dt$$

$$\Delta\theta = \frac{H}{\rho V c_p}$$

The final temperature is given by (Equation 5),

$$\theta_{final} = \theta_{preheat} + \frac{H}{m_{eq} c_p} \quad (5)$$

TABLE 1: MODEL VS. OBSERVED TEMP.

$\theta_{pre,top}$ (°C)	$Q_{frictional}$ (J)	Q_{conv} (J)	H_{total} (J)	θ_{final} (°C)	$\theta_{observed}$ (°C)
23.5	2465	191	2274	203	201
110	1471	138	1333	216	209
193	913	103	810	257	235

h = 2000W/m²C
r_{eq} = 5mm
m_{eq}: equivalent mass around heat generation area = 14g
C_p = 0.9J/gC

As the heat generated from the conduction ring allows the forming temperature to be reached more quickly, the fastener should install into the workpiece at a reduced time for a constant axial force. The external heat source reduces the amount of required frictional energy by the fastener on the workpiece as the material is becoming thermally softened. As the pre-process material temperature increases, the amount of frictional energy decreases due to thermal softening of the material. The amount of heat loss through convection decreases with an increasing pre-process material temperature due to its dominant dependency on time.

EXPERIMENTAL DESIGN

In this study, FDS experiments were conducted on Al6063 specimens at different amounts of heat input, Table 2, and the effect of resultant material temperature on process time, installation torque, and sheet separation of the FDS process were investigated. For this study, process time begins when the fastener tip touches the top surface of the material and ends when the tightening torque value is reached. The installation section of FDS is defined as the heating, penetration, extrusion forming, and thread forming phases of the process. Sheet separation is the measurable distance between the two material sheets. All experiments were conducted using a DEPRAG Flow Form Screwdriving (FFS) machine (Figure 3), and an EJOT® FDS® M5 fastener. The DEPRAG FFS machine has a spindle speed capacity of 6000rpm, fastener force capability of 2300N, and torque control up to 14Nm. A 200W capacity conduction ring heater was built into a Haysite fiberglass-reinforced thermoset support frame. The conduction ring was positioned to ensure the fastener would be installed within the inner diameter opening while the frame insulated the heat. A 130V variable transformer was included into the experimental setup to power the conduction ring.

TABLE 2: TEST MATRIX

Sample	Avg. Material Temp (^{o}C)	Spindle Speed (rpm)	Axial Force (N)	Tightening Torque (Nm)
TA1	23	6000	1650	10
TA2				
TA3				
TA4	143			
TA5				
TA6				
TA7	247			
TA8				
TA9				

FIGURE 3: DEPRAG FFS MACHINE

Two 3.4mm sheets of Al6063-T5A were combined to form a two-material stackup. Due to the joining of the two sheets during the process, a thermocouple was not able to be placed between the sheets to avoid any conflict with material flow. A thermocouple, therefore, was placed on the top surface approximately 12mm from where the outside diameter of the fastener head would be, to eliminate any conflict between the thermocouple and the downholder. The downholder displaces downwards towards the top surface of the top sheet and registers that as the 'zero-point' for the distance-controlled process. During the process, the downholder applies a force of 280N to reduce sheet separation. An additional thermocouple was placed between the bottom material and the ring heater to monitor heat source temperature (Figure 4). The average material temperature was calculated through an average of the two thermocouple readings.

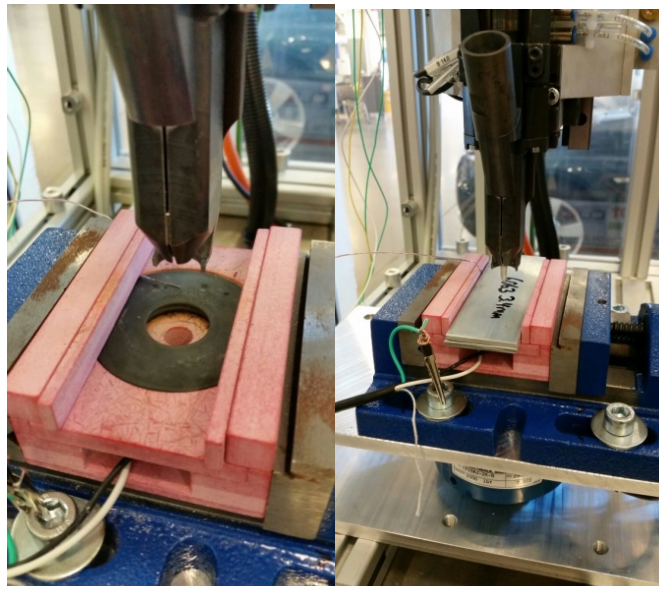

FIGURE 4: EXPERIMENTAL SETUP

The two-material stackup was placed in a Haysite fiberglass-reinforced thermoset support frame and heated to 23°C, 143°C, and 247°C. The three temperatures were chosen based on the limiting temperature of the Haysite, a room temperature baseline sample, and a mid-point between the two. The variable transformer was then switched on at a low voltage of ~40V (67W) with increasing increments until desired top surface temperature was reached. Once desired temperature was obtained, the conduction ring was switched off to stop material temperature rise, data sensors were initiated, and test was run. For this study, the fastener was installed at 6000rpm and an axial force of 1650N, the spindle speed was then lowered to 200rpm for the final tightening operation which was held at 10Nm for 1 second.

A wire electrical discharge machine was utilized to cut the sample joints along the mid-plane of the fastener. Microscope images were taken to measure the material sheet separation (Figure 5). The fastener manufacturer established a criterion whereby they recommend that any gap between the sheets be contained within the diameter of the fastener head; for this reason, sheet separation measurements were taken in-line with the head diameter.

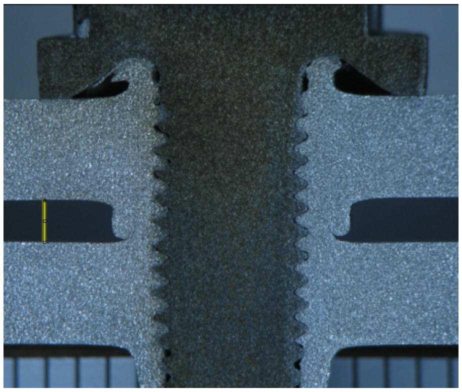

FIGURE 5: LOCATION OF MEASUREMENT FOR MATERIAL SHEET SEPARATION

RESULTS AND DISCUSSIONS

Effect of Material Temperature on Process Time

Different material temperatures are studied to minimize process time while the material temperature is still in the allowable region. At the beginning of every cycle, the equipment performs a finding process whereby the spindle rotates one full revolution to ensure the spindle is seated on the fastener head. As there are slight time differences in the finding process, this time portion has not been considered in the comparison. In the previous study [12], authors showed that holding the tightening torque at the end of the process for 1 second retained a break-loose torque of 67% compared to 57% when not holding. Break-loose torque is defined as the maximum torque required to remove the fastener after installation. As this torque-holding second is a constant step in every test and it does not affect the comparison, it is not included in the calculation of the total process time. The listed process time, therefore, includes the installation process of the fastener only.

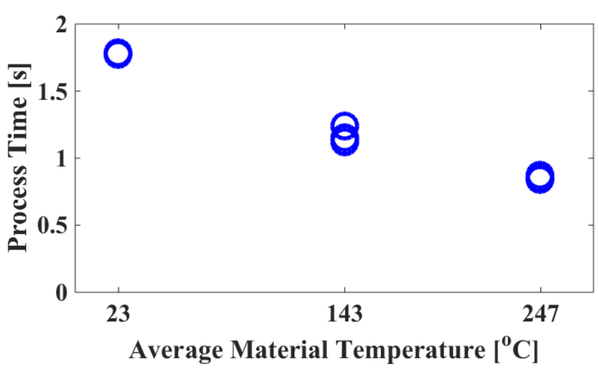

FIGURE 6: EFFECT OF INDUCED TEMPERATURE ON PROCESS TIME

It is shown in Figure 6 that as the pre-process material temperature increases, the process time decreases. As the material is thermally softened prior to installation, the fastener can penetrate and form an extrusion more quickly due to a reduction in mechanical resistance of the material. When the average material temperature is 247°C, the fastener installs 52% faster than an identical stackup at 23°C (room temperature).

Effect of Material Temperature on Maximum Installation Torque

The torque-time curves were studied to determine any effect from pre-heating the material. It was observed that as the material temperature increases, the required installation torque decreases (Figure 7). Compared to non-heated material, the maximum installation torque was reduced by 20% when the samples were heated to 247°C (Figure 8). Lowering the installation torque is advantageous as it deviates further from the minimum breaking torque of the fastener. Not only does this reduce the risk of fastener failure during installation but the tightening torque can be lowered.

The fastener manufacturer recommends that the tightening torque be selected to be 50-75% of the window between the maximum installation torque and the minimum stripping torque (Equation 1). If the installation torque can be reduced, the required tightening torque can also be reduced which further decreases total process time. For this study, however, the tightening torque was kept constant at 10Nm based on sponsor specification.

$$1.2M_{Install,max} < M_{Tightening} < 0.85M_{Stripping} \quad (1)$$

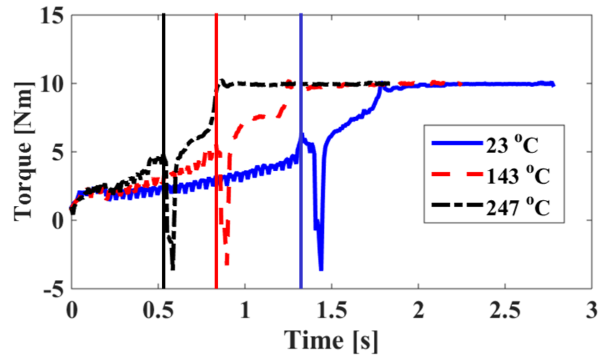

FIGURE 7: EFFECT ON MAX. INSTALLATION TORQUE

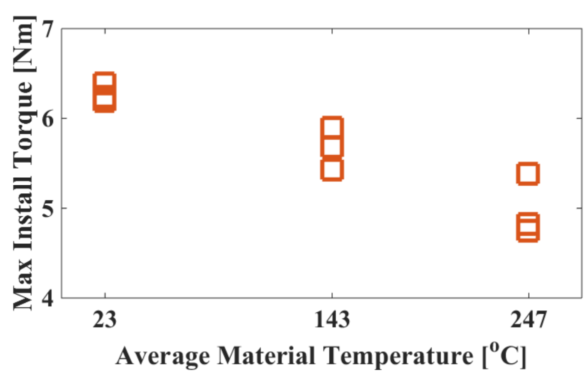

FIGURE 8: EFFECT ON MAX. INSTALLATION TORQUE

Effect of Material Temperature on Sheet Separation

A major concern when joining materials with FDS is the sheet separation that occurs due to material flow. As FDS is a forming operation and not a drilling operation, no material is removed from the stackup. The fastener installation causes the tops sheet material to flow downward and the bottom sheet material to flow upwards, this material flow forces the sheets apart. Equipment and fastener manufacturers suggest implementing a pilot (or through) hole in the top sheet to allow the bottom sheet material a place to flow. However, this eliminates an advantage of FDS where no hole alignment is necessary. One goal of adding thermal assistance to this process is aimed at reducing or even eliminating this gap. To understand the effect of material temperature on sheet separation, the distance between the material sheets is measured at each material temperature (Figure 9). A distance measurement was taken on either side of the fastener head and for each half sample cross-section, totaling four measurements per sample. As there were three replications, 12 data points were obtained for each temperature set. The average distance for the 23°C, 143°C, and 247°C samples were 1.41mm, 1.45mm, and 1.25mm, respectively (Figure 10). There is an insignificant increase of separation distance from 23°C to 143°C shown on the boxplot, where the average values fall within the spread. Aside from measurement errors, variations in original sheet thickness also contribute to this slight increase, which indicates that from 23 to 143°C, there is no thermal contribution to reducing sheet separation. The 247°C samples had significant sheet separation reduction of 11%; it is possible to reduce the sheet separation through thermal assistance to the process.

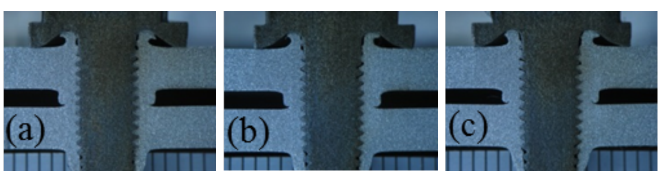

FIGURE 9: CROSS-SECTIONS OF (a) 23°C, (b) 143°C, and (c) 247°C SAMPLES

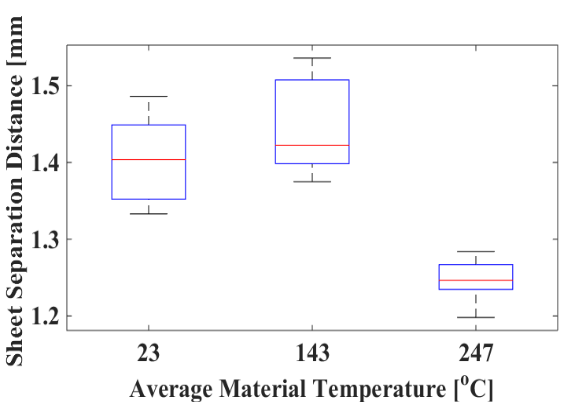

FIGURE 10: DECREASE IN SHEET SEPARATION WITH INCREASE IN TEMPERATURE

CONCLUSIONS

In this work, a study of thermal assistance to the Flow Drill Screwdriving process was presented. After performing joining experiments at different temperatures, the effects on process time and joint quality were investigated. It was shown that:

- Pre-heating the material to 247°C reduces the process time by 52% compared to that of a non-heated material.
- In addition to the significantly reduced process time, the maximum installation torque was also reduced by 20%, resulting in a cost reduction in terms of labor.
- Finally, it was shown that an 11% reduction in sheet separation was possible when the material temperature was increased using thermal assistance.

It can be concluded that the thermal assistance can aid in all aspects of the FDS process. Therefore, process time, maximum installation torque, and sheet separation studies will be conducted at elevated temperatures (>247°C) to further investigate the effect of thermal assistance and further optimize the FDS process outputs. Microhardness tests will be conducted in conjunction with these elevated temperatures to study thermal material degradation and recrystallization.

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