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RESIDUAL STRESSES IN FLOW DRILL SCREWDRIVING OF ALUMINUM ALLOY SHEETS

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ABSTRACT
With an increase in fuel economy standards and the need for reducing emissions set for the automotive sector, has resulted in the increased demand for lightweight vehicles. It is well know that the single heaviest component of a passenger vehicle is the body structure, thus has the greatest potential for significantly reducing the vehicles mass. Therefore, transitioning from steel-based bodies to ones composed of lightweight materials, such as: aluminum, magnesium and advanced high strength steels are of great interest. However, with the introduction of these new materials comes with a new means of joining, where conventional methods do not work. Therefore, this work examines a novel joining technique, flow drill screwdriving which is a thermo-mechanical process for joining aluminum and dissimilar materials. The focus of this work is to examine the residual stress distribution in a joint, because mechanical behavior and joint quality are greatly affected by the residual stress. Neutron diffraction was used for the determination of the residual stress in two samples processed with low and high fastener force. The high penetration depth of neutron radiation allows for the determination of triaxial residual stress states inside the material without destruction of the sample. It was found that the stress field around the joint location is primarily in tension, which is problematic if external forces are applied near the joint. Therefore, additional stress measurements were conducted under applied load through a lap shear test. Two load levels were applied to determine the effects on stress concentrations around the proximity of the joint.

INTRODUCTION
Flow drill screwdriving (FDS) [1] is a novel joining technology designed to address the challenges of joining aluminum sheet for automotive applications where spot welding is problematic due to chemical de-oxidation of the sheet, high energy consumption and frequent electrode changes [2]. FDS is a thermo-mechanical joining process that has evolved from friction drilling [3]. Where FDS and friction drilling both use frictional heat to soften and, thus, aid in the forming of an extrusion through a rotating conical tool. This formed extrusion increases the thread engagement for sheet metal, further increasing the tightening torque, clamping load and overall reliability of the joint. For friction drilling, after the extrusion is formed the process is completed. Therefore, another process is required to tap the extrusion and a second to install a fastener. All of these additional processes adds significant time to the overall fastening process, which is critical for the automotive sector. The FDS process, on the other hand, combines these additional steps into a single operation, thus saving costly time.

The FDS process involves six steps, as displayed schematically in Figure 1, which are: heating, penetration, extrusion forming, thread forming, screwdriving and final tightening torque. The fastener is first rotated at high speeds while in contact with the top sheet of the workpiece, creating localized softening of the material via frictional heat generation (step 1: heating). The rotational speed is accompanied by a downward force, causing the fastener to easily pierce the already softened workpiece (step 2: penetration). The material then flows axially around the fastener and forms the extrusion on the bottom sheet of the workpiece (step 3: extrusion forming). The fastener is designed to have tapered threads, so that as the fastener is driven further into the workpiece the threads are formed while the material is still in a softened state (step 4: thread forming). With further driving, the threads are fully formed within the workpiece and engaged with the fastener (step 5: screwdriving). Then the rotational speed is lowered when the fasteners head makes contact with the top sheet and a final torque is applied to a preset value (step 6: final tightening torque).

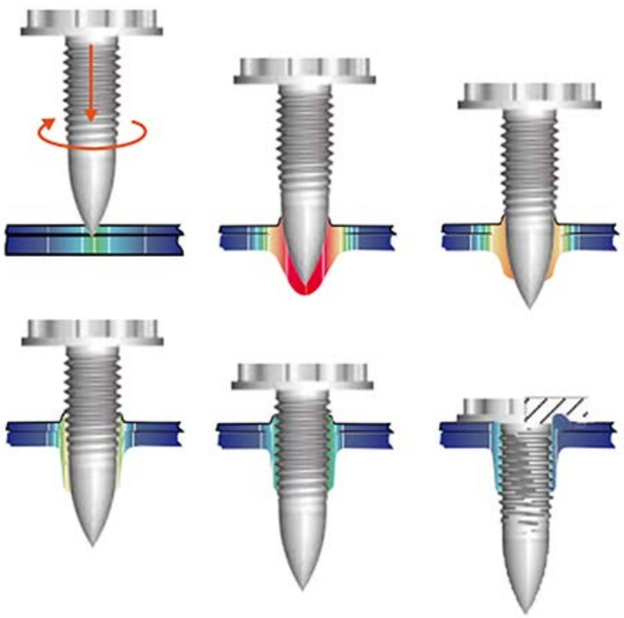

Figure 1: A schematic of the flow drill screwing (FDS) process [1].

In addition, FDS is a single sided joining technique, when the workpiece is adequately ridged (low rigidity can cause bending near the joint). This is beneficial for aluminum intensive auto bodies, due to aluminum tubing/box extrusions used extensively, where two sided joining techniques do not have access to both sides, such as: clinching [4], [5] and self-piercing rivets [6], [7]. Furthermore, FDS is capable for joining dissimilar metals and even composites with minimal preparation of the material. However, with the many benefits of FDS little research has been conducted on the process and the corresponding quality of the joint.

For a specific joining process considerations of speed and cost are front and center; the residual stresses become important because of their role regarding the strength of the joint and its fatigue properties. Residual stresses originate from two main sources: a) the difference in thermal expansion coefficients between steel and aluminum ($CTE_{Al} \approx 2 \times CTE_{steel}$) and b) the displacement of aluminum through plastic flow. The interplay between the two effects has not been analyzed yet which emphasizes the need for experimental data even more. Stress characterization of the FDS joint is done best non-destructively through diffraction which analyzes the spatial and orientation distribution of elastic lattice strains in the aluminum sheet.

The scope of this work is to characterize, for the first time, the residual stress field around a FDS joint. And to explore the role of processing parameters, particularly down force, on the resultant residual stresses.

EXPERIMENTAL PROCEDURE

FDS experiments were conducted on two aluminum alloy AL6063-T5A sheets with a thickness of 3.2 mm each, with neither having a pilot/through-hole. Al6063-T5A was selected as the candidate material due to its widely-adopted use in the BiW (Body-in-White) for the automobile industry. All experiments were conducted using a DEPRAG Flow Drill Screwdriving machine, displayed in Figure 2, and an EJOT® FDS® M5 fastener with an overall length of ~30 mm. The DEPRAG® FDS machine has a spindle speed capacity of 6000 rpm, fastener force capability of 2300 N, and torque control up to 15 N-m.

Figure 2: DEPRAG FDS experimental setup.

In this study, two FDS samples were prepared with a constant rotational speed of 6000 rpm and a final tightening torque of 8 Nm. The fastener force, however, was varied as the differentiator. The first sample was processed with a fastener force of 1325 N and the second at 2167 N, which corresponds to approximately 58 percent and 94 percent of the fastener force capacity of the FDS machine, respectively. These test conditions were chosen because of the thought that this parameter has the largest effect on residual stresses on the joint and the fact that fastener force directly correlates to fastener cycle time, which is of the upmost importance to the automotive industry. Fastener force, when comparing between low and high levels, effects the residual stresses around the joint due to various levels of heat input. At low fastener force levels leads to increased cycle time and, thus, increases the frictional heat generation. Whereas, the opposite is seen during high levels of fastener force, which has lower cycle times and frictional heat generation during the FDS process.

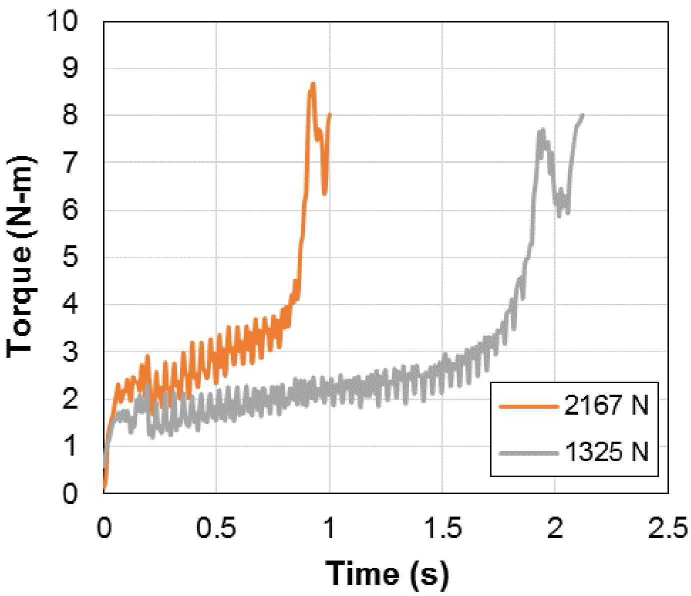

Figure 3: Torque vs time graph of the FDS samples processed at low (1325 N) and high (2167 N) fastener force levels.

Torque-time data from the two data sets are shown in Figure 3 with, as expected, the higher fastener force leading to a shorter process time. The samples created with a fastener force of 1325 N had a process time of 2.12 s while the increased fastener force of 2167 N had a shorter process time of 1.01 s, a 52% reduction. Installation torque during the FDS process is classified as the required torque to thread-form the workpiece and can be identified by the spike prior to the final tightening torque. The installation torque is important to identify as elevated values may be more at risk for fastener failure during installation. The installation torque is inversely related to the temperature of the material, a softener material will have a lower installation torque. As the lowered fastener force leads to higher temperatures, a lower installation torque is observed. The high fastener force of 2167 N had an installation torque of 8.66 Nm while the low fastener force of 1325 N had an installation torque of 7.65 Nm, this corresponds to a 12% reduction in the final torque level.

Triaxial neutron strain scanning has been performed at the BT8 neutron diffractometer at the NIST Center for Neutron Research. A wavelength of 1.735 Å was chosen such that the (3 1 1) lattice planes of the *fcc* aluminum alloy was approximately at $2\theta = 90.5°$. Measurements were carried out at the half-sheet thickness in the top and bottom sheets of the FDS samples. The measurements were completed at an interval of 1 mm, starting at 1 mm from the screw interface with a cubic gauge volume of $2 \, x \, 2 \, x \, 2$ mm^3. Due to strong preferred orientation of the aluminum, measurements could not be done along the principle directions of the sheet; instead, directions of strong intensity for the (3 1 1) reflection were used, which were determined from pole figure analysis of the base material.

Two scans were conducted per sample and per sheet along the rolling direction (RD) and transvers direction (TD), with respect to the samples sheet orientation. For simplicity, and because the aluminum sheet is elastically nearly isotropic, the system is considered to have rotational symmetry. Therefore, the RD and TD scans was averaged together which also increases the counting statistics. This averaging of the two scan directions resulted in an equivalent radial and hoop stresses for the respective sheet. In addition to the FDS samples, a conventional M5 cap screw; drilled, tapped and torqued to 4.6 Nm in a single sheet (3.2 mm thickness) was measured for comparison of the stress field around the joint.

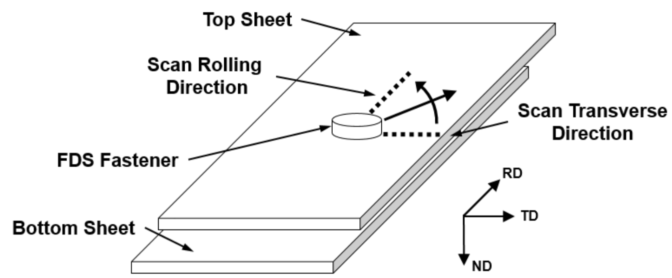

Figure 4: Schematic of the FDS sample showing scan locations (not drawn to scale).

RESULTS AND DISCUSSION

The residual stress components, determined by neutron diffraction, of the FDS joint for low and high fastener force are shown in Figure 5 and Figure 6, along with the conventional M5 screw joint without applied fastener force and no heating involved. The error bars in the figures represent one standard deviation. It can be seen that magnitude of the residual stress is much larger for the FDS joints as compared to the conventional (drill and tap) joint. In general, the stresses of the analyzed joints trend to zero, which is expected further away from the joint location.

When analyzing the top sheet, the stresses are in tension for the FDS joints whereas the stresses for the conventional M5 screw joint are in slight compression (-16 MPa) in the radial direction. Moreover, the radial stresses for the high fastener force (2167 N) sample are greater as compared to the low fastener force (1325 N) sample, where maximum tensile stresses are approximately 125 MPa and 42 MPa, respectively. As for the hoop stresses measured in the top sheet, a similar trend is seen as with the radial stresses; however, the conventional M5 screw joint is also in tension. The magnitude of the hoop stresses are also greater than the radial stresses, where the maximum stress for the samples are approximately 37 MPa, 69 MPa and 160 MPa with respect to the conventional M5 screw, FDS with low fastener force and FDS with high fastener force. This increase in stress for the FDS joint with high fastener force is most likely due to lower frictional heat generation as compared to the low fastener force sample.

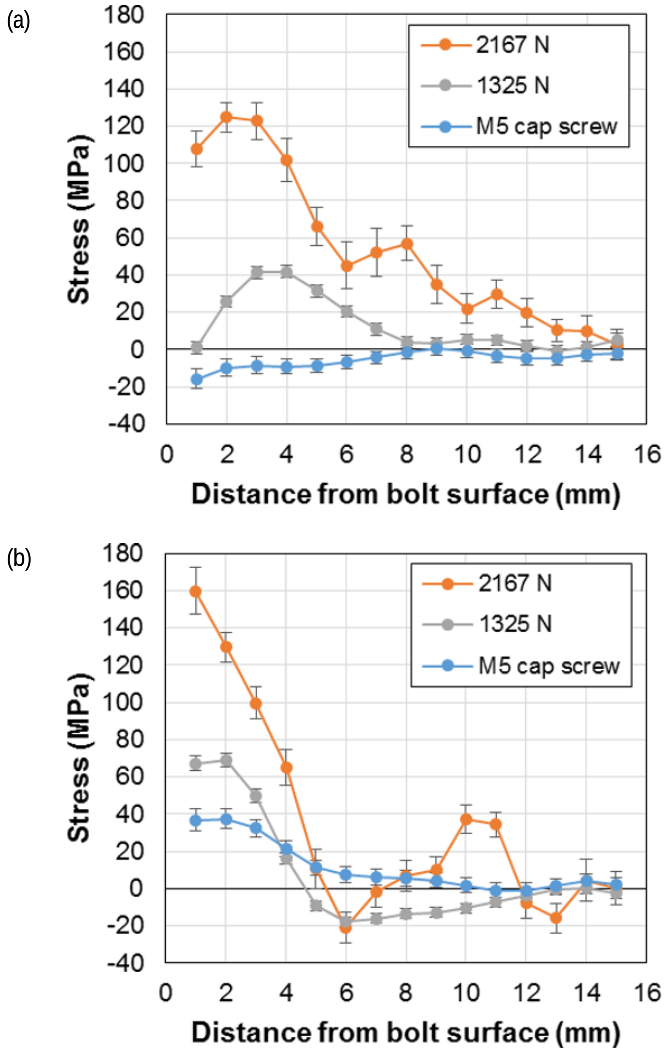

Figure 5: Residual stresses for the top sheet and for different down forces in the (a) radial direction and (b) hoop direction. For comparison, a conventional M5 screw joint is also shown.

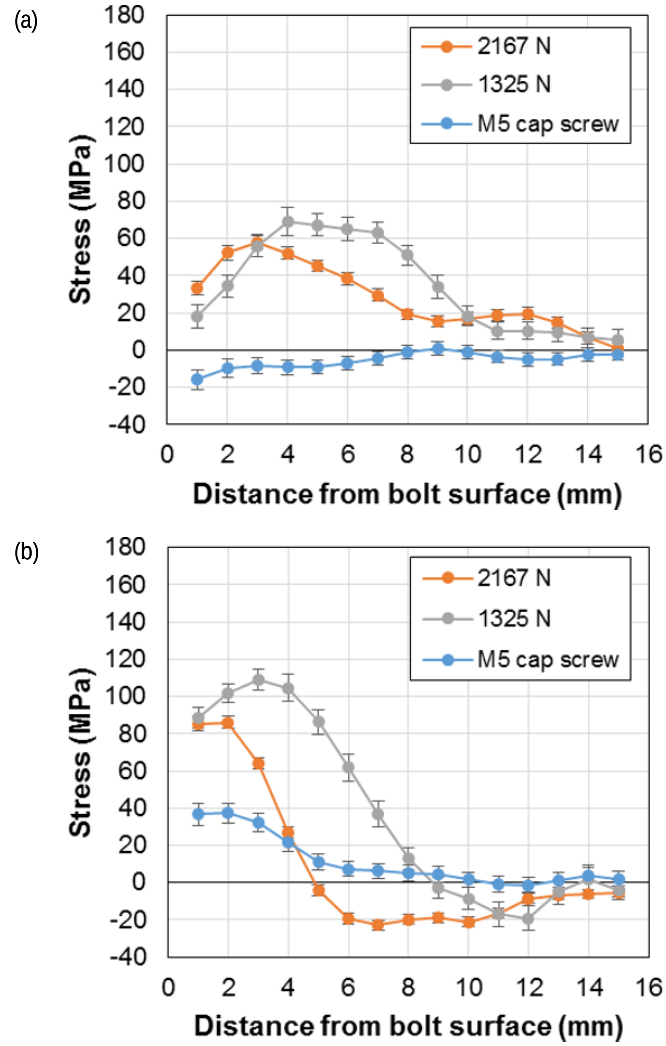

Figure 6: Residual stresses for the bottom sheet and for different down forces in the (a) radial direction and (b) hoop direction. For comparison, a conventional M5 screw joint is also shown.

The bottom sheet stresses are similar to that seen in the top sheet, where the stresses are in tension and that the stresses in the hoop direction are greater than that of the radial direction for the FDS joints. However, the stress magnitude in the high fastener force joint is lower than that seen in the low fastener force joint for both the radial and hoop directions. Furthermore, the overall stresses in the bottom sheet is higher than that seen in the top sheet for the low fastener force sample. However, the opposite is true for the high fastener force sample, where the bottom sheet stresses are lower than the top sheet stresses. For the low fastener force sample, the stresses increased to a maximum of 69 MPa and 109 MPa in the radial and hoop directions, respectively. The high fastener force sample, on the other hand, showed decreased maximum stress in the radial direction to 58 MPa and in the hoop direction to 86 MPa.

Overall, these stresses are problematic for joints, if applied loads produce stress concentrations in the proximity of the joint locations; superposition of existing residual stresses can quickly reach yield and/or lead to unsatisfactory fatigue behavior. Therefore, neutron stress measurements were conducted under applied load.

Figure 7 displays the schematic of the lap shear test, where the top and bottom sheets are pulled in opposite directions. Two loading conditions were measured, where the gross applied stress was 23 MPa and 40 MPa, which corresponds to an applied load of 3 kN and 5 kN, respectively. Neutron measurements under load were conducted in the same manner as the unloaded measurements. Measurements were conducted on the low fastener force FDS sample (1325 kN). Scans were conducted along the RD and TD in the top and bottom sheet as displayed in Figure 7 (TD scans are along the out-of-page direction).

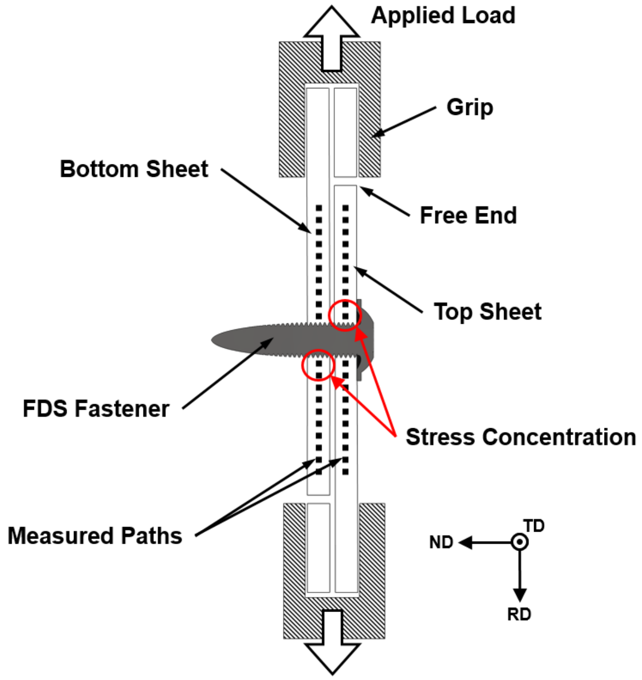

Figure 7: Schematic of the lap shear test showing regions of stress concentrations (not drawn to scale).

Sheets under applied load that have geometrical inhomogeneities such as holes with tight fitting pins 'see' a concentration of stress around these inhomogeneities; for this case, the analytical solution predicts that the superimposed external stress is compressive with a magnitude of -4 times the applied stress around the contact region where the pin radius vector is parallel to the applied load. Numerical solutions for loading of a tight fitting pin [8] find smaller factors around -1.2 for the radial stress and 0.5 for the hoop stress which would add to the existing residual stress. However, our sample is somewhat different from the ideal case in that it has both axial 'clamping' near the threaded region and the increased sheet thickness near the bolt interface. The analytical solution and the numeric simulation do not include residual stresses, and it is assumed that applied stresses (including stress concentrations) are added to the residual stresses as long as the yield point is not exceeded. The resultant total stress is shown in Figure 8.

The total radial stress in the top sheet, measured along the RD, is shown in Figure 8(a). This corresponds to the applied load end of the sheet, or in other words, should see the addition of the applied tensile stress to the residual stress. Since the radial stresses are in tension for the unloaded state, the applied tensile stress will add to equal the total stress. The resultant measurements show this to be true, where both load steps adds to the residual stress. Furthermore, the effected stress field is larger than the unloaded state, where beyond 14 mm from the bolt surface the total stress settles to the applied stress levels.

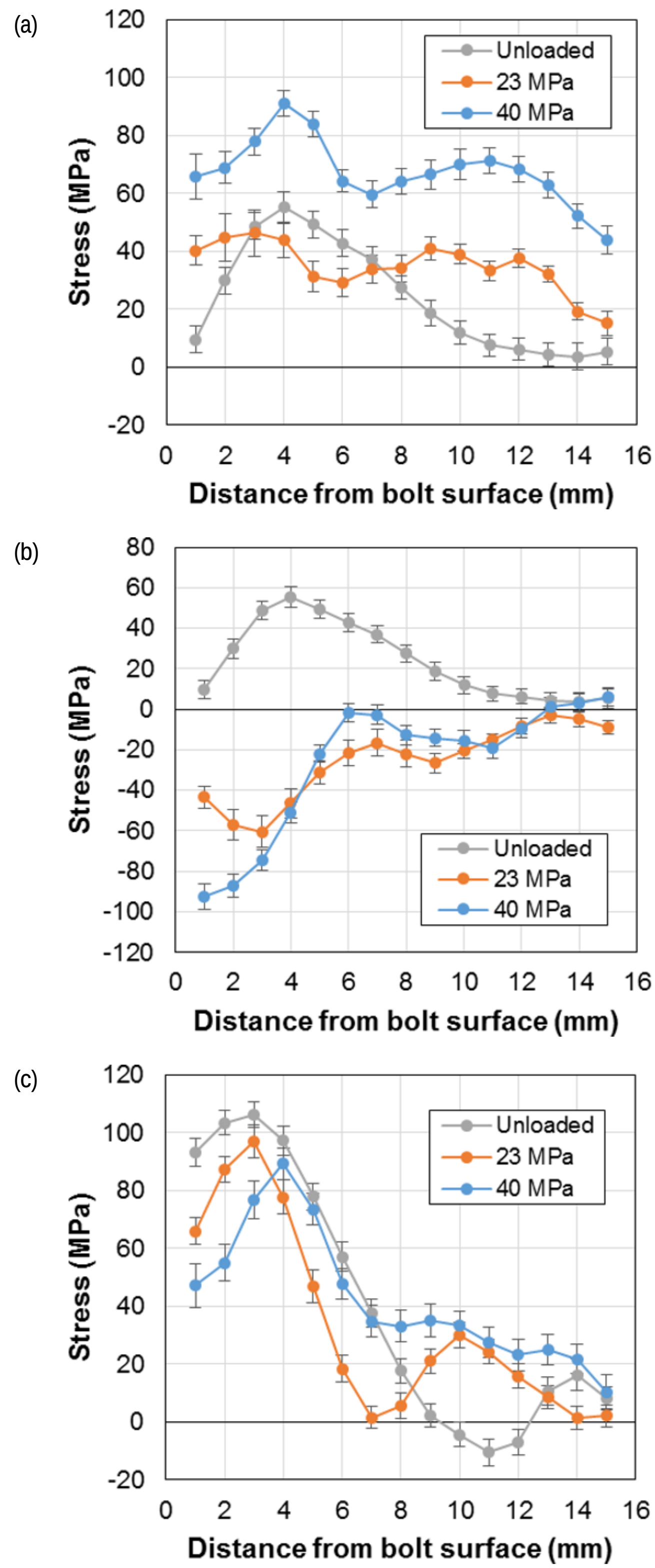

Figure 8: (a) Radial stresses along the RD line for the top sheet (applied stress end), (b) radial stresses along the RD line for the bottom sheet (free end) and (c) hoop stresses along the TD line (stresses are in the RD of the sheet).

On the other hand, the total radial stresses in the bottom sheet become compressive overall, as shown in Figure 8(b), due to the compressive nature of the stress concentration from the applied load. The applied stress of 23 MPa caused a compressive stress of -43 MPa, whereas the applied stress of 40 MPa caused a compressive stress of -93 MPa near the bolt surface. When compared to the unloaded state (10 MPa near the bolt surface), the stress concentration factor is 2.3 and 2.6 for the applied stress of 23 MPa and 40 MPa, respectively. This reduction is not nearly as big as expected for the analytical solution ($-4 \times \sigma_{appl}$) and larger than the numerical one ($-1.2 \times \sigma_{appl}$). Furthermore, the observed hoop stress reduction does not agree with the calculation which predicts that about 50% of the applied tensile stress is added to the residual stress as seen in Figure 8(c). This disagreement with the theoretical predictions of the stress concentrations, made for simpler geometries, do not match the experimental findings. This may be due to thread and the increased sheet thickness from the thread extrusion.

SUMMARY AND CONCLUSIONS

The findings presented here are the first glimpse into residual stress distributions for the FDS joints produced with low and high fastener force. It has been found that the FDS process induces a tensile residual stress in radial and hoop direction in the immediate vicinity of the joint. Furthermore, with high fastener force levels increase the tensile residual stresses in the top sheet when compared to the bottom sheet. However, the opposite is seen for low fastener force levels where the tensile residual stresses are lower in the top sheet as compared to the bottom sheet. This is due to the thermodynamics of the processing and needs to be further examined, to produce the highest quality of joints with minimum tensile residual stress or even compressive stresses, which is beneficial for fatigue life of the joint.

In addition, these findings are the first tests performed on an FDS joint while under applied load with in-situ neutron diffraction. It was found that theoretical predictions of stress concentrations made for simpler geometries do not provide an accurate description of the experimental results, thus highlighting the need for tailored theoretical solutions that also include the effects of the thread and the increased effective sheet thickness around the screw.

DISCLAMER

Certain commercial firms and trade names are identified in this report in order to specify aspects of the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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