Thermal-induced Residual Stresses and Distortions in Friction Stir Welds - A Literature Review

Mohamed H. El-Moayed*, Ahmed Y. Shash^{*,**,*†}, Mahmoud Abd Rabou^{*,***},
and Mahmoud G. El-Sherbiny*

*Mechanical Design and Production Department, Faculty of Engineering, Cairo University, Giza, 12613, Egypt

**Faculty of Engineering and Materials Science, German University in Cairo, New Cairo, 11835, Egypt

***Faculty of Engineering, Zewail City of Science and Technology, Giza, 11341, Egypt

[†]Corresponding author: ahmed.shash@cu.edu.eg, ahmed.shash@guc.edu.eg

(Received March 11, 2021; Revised April 28, 2021; Accepted June 3, 2021)

Abstract

Friction Stir Welding (FSW) is a solid-state welding technique that uses the heat generated from friction to assemble a wide variety of materials. Irrespective of having a lower heat input as compared to conventional welding techniques, friction stir welds are still prone to significant thermal-induced stresses and distortions owing to the uneven heating and cooling cycles that a weld goes through. Surprisingly, not several reviews have addressed both the residual stresses and distortions of friction stir welds despite their crucial impact on the weld performance. Therefore, the current paper reviews their development, their correlation with process parameters, and ways to reduce them. Moreover, it explains the current status of process modeling and research gaps in the area of interest.

Key Words: Friction stir welding, Residual stresses, Distortion, Numerical modeling, Review

1. Introduction

Uneven heating and cooling cycles can leave a welded joint susceptible to significant residual stresses. Those stresses switch from tension to compression along the transverse direction, which, in some cases, can cause unwanted irregularities in the welded component. Dealing with the resulting irregularities is an expensive and time-consuming process. Unfortunately, owing to the welding process nature, the formation of residual stresses and their side-effects is inevitable and cannot be prevented. However, it can be controlled via process input parameters - the ones that affect the amount of heat input directly.

Residual stresses and distortions in friction stir welds, also known as the “residual states”, have been investigated over the years, and many conclusions have been published. Nevertheless, the amount of research done in this area is still limited as compared to the amount of research devoted to investigating the effect of the process parameters on the mechanical properties. The same

applies to the review articles publishing status over the past ten years. The authors herein are not trying to undermine the importance of analyzing process inputs-outputs correlations. They are, however, trying to bring a refreshing perspective to the field regarding this topic.

In 2011, Woo et al.¹⁾ reviewed residual stress measurement by Neutron diffraction. They covered its theoretical background, practical issues, and applications. In 2015, on the other hand, Hattel et al.²⁾ reviewed the different modeling techniques of the residual stresses. Besides these two studies, the authors could not find any more reviews on welding-induced stresses. Moreover, no review to date has addressed thermal distortion in friction stir welds. Accordingly, the current paper is dedicated to covering the following topics:

- Residual states development,
- Effect of process parameters on residual states,
- Residual states mitigation techniques,
- Process modeling, and
- Research gaps.

2. Residual States Development

Kumar et al.³⁾ explained in their book how residual stresses develop in the first place. Their demonstration was used as a reference in the current section. Fig. 1 shows an illustration of residual stress development in friction stir welds. In Fig. 1a, the green rectangle represents the portion of the base material to be welded, while the blue ones represent the portions that will not undergo any changes. The latter acts as rigid constraints to the former, preventing it from free expansion/ contraction.

During welding, the green region experiences a large amount of heat input for being in direct contact with the tool. As mentioned above, this region cannot expand freely due to its interaction with the adjacent material. Consequently, a compressive mechanical strain (ϵ_{mec}) is introduced at T_1 , the peak welding temperature. Its value is equal to C , which is the same value of the thermal strain (ϵ_{th}) developed in the case of free thermal expansion at the same temperature (see Fig. 1b). If C is lower than the yield strain of the material, no dimensional changes will occur in the nugget zone (NZ). Otherwise, plastic deformation occurs, causing a permanent shape change.

Fig. 1c depicts the cooling stage during which the NZ would shrink if it were not for the rigid constraints. In other words, the adjacent material stretches the NZ from the position where it was allowed to shrink by strain C to the position where it does not shrink due to the presence of rigid constraints. Therefore, the NZ de-

Fig. 1 Residual stress development illustration

velops tensile stresses, reflecting its state. If the strain value outreaches the yield limit, lower tensile stresses are obtained due to stress relaxation triggered by permanent deformation.

In the absence of external constraints, the total sum of body forces must equal zero. Hence, the adjacent material forms compressive stresses to balance their tensile counterparts. Fig. 1d shows a typical residual stress distribution in the transverse direction. When compressive stresses exceed the critical buckling limit of the sheet, buckling distortion becomes inevitable upon de-clamping.

3. Effect of Process Parameters on Residual States

Residual properties are highly affected by the process parameters, especially the ones affecting the amount of heat input directly. So, it is no surprise that researchers have been investigating the effects of primary process parameters for the past few years. Parameters like rotational and traverse speeds are the most widely investigated ones, as proven in the next paragraphs.

He et al.⁴⁾ investigated the effect of rotational speed on longitudinal tensile residual stress in thick AA6061 friction stir welds. Their results showed that residual stress slightly increased with increasing the rotational speed, which was the opposite of what Tutum and Hattel⁵⁾ reported. This increase was attributed to the high temperatures associated with high rotational speeds. Also, all stress distributions were double-peaked, shaped like an “M.” The same observation was made back in 2003 by Peel et al.⁶⁾, who studied the effect of traverse speed on residual stresses in AA5083 welds. Fig. 2 demonstrates the M-shaped residual stress profiles extracted from⁴⁾.

Meanwhile, Peel et al.⁶⁾ reported a positive correlation between longitudinal tensile residual stress and traverse speed. Feng et al.⁷⁾, Tutum and Hattel⁵⁾, and Farajkhah and Liu⁸⁾ published an equivalent conclusion in their studies. They all agree that large heat input associated with low traverse speeds results in a more uniform thermal gradient along the transverse direction, causing a

Fig. 2 Longitudinal residual stress distributions

Fig. 3 Residual stress at different operating conditions

lower thermal contraction mismatch between the HAZ and adjacent material during cooling. Hence, reduced tensile residual stresses are obtained at low speeds and vice versa. Fig. 3 highlights the relationship between longitudinal residual stress and operating speeds.

While several authors claim that increasing the traverse speed increases the longitudinal tensile residual stress, others claim the opposite. Buffa et al.⁹⁾ and Camilleri et al.¹⁰⁾ mentioned in their studies that the correlation did not have to be always positive. However, no detailed explanation was provided by both research groups. Their statement should be taken with caution as not many publications reported such an observation.

The above-mentioned studies were mainly focused on longitudinal tensile residual stress in friction stir welds. Regarding out-of-plane distortion, not only is it influenced by processing speeds, but also sheet dimensions. Shi et al.¹¹⁾ explored the effects of rotational speed, traverse speed, and sheet length on the geometric imperfection of AA6013 panels. Their experiments showed that increasing the rotational speed and sheet length could increase the distortion. Meanwhile, traverse speed did not show any significance whatsoever. Likewise, Zhang et al.¹²⁾ conducted a computational investigation of the size effects on AA6061 residual states. They concluded that sheet width had more control over distortion than the length, which was similar to what Costa et al.¹³⁾ published recently.

According to most distortion-related studies¹¹⁻¹⁵⁾, friction stir welded sheets exhibit an “anti-saddle” pattern after de-clamping. In other words, they become concave in the transverse direction and convex in the longitudinal direction¹⁴⁾. Shi et al.¹¹⁾ attributed the reversed saddle profile to the extension difference between the top and bottom sheet layers. During welding, the top layer is extruded by the tool in the welding direction, unlike the bottom layer, which is in almost rigid contact with the backing plate and cannot experience such interaction. Fig. 4 demonstrates the typical distortion shape after the FSW process.

Fig. 4 Typical distortion shape of friction-stir welds

4. Residual States Mitigation Techniques

The formation of residual properties cannot be prevented but can be controlled by process input parameters to a certain limit. Beyond this limit, the residuals cannot be reduced further without the need for secondary thermal/mechanical loads. Hattel et al.²⁾ listed in their review four reduction techniques that were proposed by other researchers over time. The techniques are:

1. Thermal Tensioning,
2. Mechanical Tensioning,
3. Surface Treatment, and
4. Post-Weld Direct Rolling

4.1 Thermal Tensioning

The general idea of “Thermal Tensioning” is to stretch the weld zone before or during welding by imposing a preset temperature gradient^{16,17)}. This thermal difference should allow for more expansion of the weld zone, thereby reducing its plasticity, which is the source of residual stresses and distortions¹⁸⁾. The technique can be implemented statically or dynamically. The former is referred to as “Steady-State Thermal Tensioning, STT,” while the latter is known as “Transient Thermal Tensioning, TTT.” Fig. 5 displays the difference between

Fig. 5 Thermal tensioning technique, (a) Steady-State Thermal Tensioning (STT), (b) Transient Thermal Tensioning (TTT)

STT and TTT.

STT requires a combination of cooling and heating before and during welding. According to Michaleris and Sun¹⁶⁾, STT with elastic pre-bending could minimize buckling and angular distortions of AH36 steel panels. The downside of STT is the cost of the apparatus, making it impractical for industrial applications²⁾. TTT, on the other hand, does not have this limitation. In TTT, two moving heat sources are applied to each side of the main torch during welding only, which cuts the cooling equipment costs. Despite its cost-effectiveness, TTT is a complex optimization problem, as presented by Michaleris et al.¹⁷⁾, that involves intense computational runs to determine the optimum size and intensity of heating bands as well as their distances from the main torch. It is worth mentioning that little to no work has addressed STT and TTT applicability to the FSW process.

4.2 Mechanical Tensioning

The general idea of “Mechanical Tensioning, MT” is very similar to that of “Thermal Tensioning.” However, instead of stretching the part thermally, it is clamped from one end and pulled mechanically from the opposite side. The mechanical pull must remain uniform before and during welding. Fig. 6 shows a schematic representation of the technique. According to Price et al.¹⁹⁾, MT was successful in flattening the residual stress profile and, hence, eliminating buckling distortion of AA2024 sheets. Nevertheless, like STT, MT is not widely used due to the expense of its equipment¹⁸⁾.

4.3 Surface Treatment

The surface treatment takes on many forms. Some of which are shot, laser, and needle peening. They all share the concept of introducing single or multiple layers of compressive residual stress near the part's surface by impact. The source and mechanism of impact are what differentiate one form from another. Fig. 7 highlights the difference between the above-mentioned forms. The compressive pressure wave in shot and needle peening is formed by mechanical impact. On the

Fig. 6 Mechanical tensioning process

Fig. 7 Surface treatment processes, (a) Shot peening, (b) Laser peening, (c) Needle peening.

other hand, in laser peening, the pressure is formed by the rapidly expanding plasma trapped between the workpiece and the tamping layer²⁰⁾.

Hatamleh et al.²¹⁾ highlighted the ability of laser peening to enhance the mechanical properties of AA7075 friction stir welds. Moreover, they stated that shot peening had minimal effect on the properties compared to its laser counterpart. For AA2024 sheets, Larose et al.²²⁾ managed to reduce the distortion with needle peening by 37 % and 82 % in both transverse and longitudinal directions, respectively. With their study, they introduced needle peening as an effective mitigation technique.

4.4 Post-Weld Direct Rolling

As the name implies, Post-Weld Direct Rolling (PWDR) is a mitigation technique that takes place after the welding process is done. As shown in Fig. 8, a roller is pressed against the weld and moved in the longitudinal direction. When the weld is squeezed in the thickness direction, it elongates in the other two directions due to volume constancy. Furthermore, tensile residual stresses are relieved and become compressive. The magnitude of rolling-induced compressive stresses depends on the roller size and downward force. Based on the results from Altenkirch et al.²³⁾ and Wen et al.²⁴⁾, PWDR is a very enabling technology with great potential in the aerospace sector.

Fig. 8 Post-weld direct rolling

Fig. 9 Stationary shoulder friction stir welding

4.5 Stationary Shoulder Friction Stir Welding

Stationary Shoulder Friction Stir Welding (SSFSW) is a relatively new variant of the conventional FSW process.

Its tool consists of a pin that rotates independently of its shoulder (see Fig. 9). The external stationary shoulder absorbs a large portion of frictional heat, thereby reducing the peak welding temperature. Hence, a narrower NZ and tensile region are obtained. Recent studies²⁵⁻²⁷⁾ reported promising results regarding the capability of SSFSW as an in-situation mitigation technique. As compared to other techniques, SSFSW does not require expensive apparatus, making it practical for both research and industrial applications.

5. Residual States Modeling Status

Finite Element Modeling (FEM) has always been a useful tool for analyzing different aspects of the FSW process, such as transient temperature fields, thermal-induced stress fields, and material flow patterns. The reason is that FEM can obtain instantaneous results and save research time and cost. Table 1 lists a few ex-

Table 1 Examples of FE models developed by different authors over the years

Authors	Year	Form.	Sym.	Field output				
				Temp.	SS	Distort.	Mat. Flow	Met.
Frigaard et al. ²⁸⁾	2001	-	No	☐				☐
Chao et al. ²⁹⁾	2003	L	Yes	☐				
Chen and Kovacevic ³⁰⁾	2003	L	Yes	☐	☐			
Khandkar et al. ³¹⁾	2003	L	No	☐				
Song and Kovacevic ³²⁾	2003	L	Yes	☐				
Deng and Xu ³³⁾	2004	ALE	No	☐			☐	
Zhu and Chao ³⁴⁾	2004	L	Yes	☐	☐			
Chao et al. ³⁵⁾	2005	CEL	No	☐			☐	
Fratini and Buffa ³⁶⁾	2005	ALE	No					☐
Schmidt and Hattel ³⁷⁾	2005	ALE	No	☐			☐	
Soundararajan et al. ³⁸⁾	2005	L	No	☐	☐			
Heurtier et al. ³⁹⁾	2006	-	No	☐			☐	☐
Khandkar et al. ⁴⁰⁾	2006	L	No	☐	☐			
Uyyuru and Kailas ⁴¹⁾	2006	L	No	☐	☐		☐	
Feng et al. ⁷⁾	2007	L	Yes	☐	☐			☐
Murphy et al. ⁴²⁾	2007	L	No	☐	☐	☐		
Zhang et al. ⁴³⁾	2007	ALE	No	☐			☐	
Bastier et al. ⁴⁴⁾	2008	ALE	No	☐	☐	☐		☐
Schmidt and Hattel ⁴⁵⁾	2008	CFD	No	☐				
Qin and Michaleris ⁴⁶⁾	2009	CEL	No	☐	☐			
Assidi et al. ⁴⁷⁾	2010	ALE	No	☐				
Prasanna et al. ⁴⁸⁾	2010	-	No	☐				
Richards et al. ⁴⁹⁾	2010	L	No	☐	☐	☐		
Tutum and Hattel ⁵⁾	2010	L	Yes	☐	☐			
Wang et al. ⁵⁰⁾	2010	L	No	☐	☐			

Table 1 (Cont.)

Authors	Year	Form.	Sym.	Field output				
				Temp.	SS	Distort.	Mat. Flow	Met.
Buffa et al. ⁹⁾	2011	L	No	☐	☐			
Jacquín et al. ⁵¹⁾	2011	CEL	No	☐			☐	
Riahi and Nazari ⁵²⁾	2011	L	No	☐	☐			
Yan et al. ¹⁴⁾	2011	L	No	☐	☐	☐		
Aval et al. ⁵³⁾	2012	ALE	No	☐	☐			
McCune et al. ¹⁵⁾	2012	L	No	☐	☐	☐		
Al-Badour et al. ⁵⁴⁾	2013	CEL	No				☐	
Mun and Seo ⁵⁵⁾	2013	L	Yes	☐	☐	☐		
Sonne et al. ⁵⁶⁾	2013	L	Yes	☐	☐			☐
Darvazi and Iranmanesh ⁵⁷⁾	2014	L	No	☐	☐			
Shi et al. ⁵⁸⁾	2014	CEL	No	☐			☐	
Zhang et al. ¹²⁾	2014	L	No	☐	☐	☐		
Camilleri et al. ¹⁰⁾	2015	L	No	☐	☐	☐		
Casavola et al. ⁵⁹⁾	2015	L	Yes	☐	☐			
Shi et al. ⁶⁰⁾	2015	CFD	No	☐			☐	
Asadi et al. ⁶¹⁾	2016	-	No	☐				☐
Aziz et al. ⁶²⁾	2016	ALE	No	☐				
Bachmann et al. ⁶³⁾	2017	L	Yes	☐	☐			☐
Dialami et al. ⁶⁴⁾	2017	ALE	No	☐	☐			
Farajkhah and Liu ⁸⁾	2017	L	No	☐	☐			
Hou et al. ⁶⁵⁾	2018	CEL	No	☐	☐			
Yu et al. ⁶⁶⁾	2018	L	No	☐	☐			
Costa et al. ¹³⁾	2019	L	Yes	☐	☐	☐		
He et al. ²⁵⁾	2019	L	No	☐	☐	☐		
Salimi et al. ⁶⁷⁾	2019	CEL	No	☐	☐			
Zhang et al. ⁶⁸⁾	2019	L	Yes	☐	☐			
Xu et al. ⁶⁹⁾	2020	L	No	☐	☐			
Yu et al. ⁷⁰⁾	2020	L	No	☐	☐	☐		

amples from the literature.

By analyzing the data in Table 1, it can be concluded that transient heat transfer is the most numerically investigated process aspect. The same applies to active/residual stress analysis. On the other hand, the total number of numerical studies dedicated to out-of-plane distortion, material flow, and metallurgical properties, such as hardness and grain size, is still deficient, as shown in Fig. 10. The degree of complexity and computational cost are the main constraints of these kinds of studies. It can also be concluded that only 23 % of researchers have considered symmetry in their publications regardless of the asymmetric nature of the FSW process. According to McCune et al.¹⁵⁾, the asym-

Fig. 10 Frequency analysis of the numerical studies conducted within the past 20 years

metrical variations caused by the tool torque have an insignificant effect on heat and stress distributions.

6. Conclusions

The current literature review was mainly focused on welding-induced residual stress and distortion development, controlling parameters, and mitigation techniques. It also reflected on the present status of the FSW process modeling. In light of the gathered information, five literature gaps were discovered. First, little to no work has addressed the effects of tool geometry, tilt angle, and plunge depth on the residual states of friction stir welds. Second, no study to date has examined the statistical significance of process parameters plus their interactions in affecting welds' residual properties. Third, no study, to our knowledge, has discussed the applicability of thermal tensioning to the FSW process. Fourth, SSFSW is a promising mitigation technique that still requires a thorough investigation. Fifth, only a few numerical models have been developed to predict out-of-plane distortion, material flow patterns, and metallurgical properties of friction stir welds.

ORCID: Mohamed H. El-Mayed: <https://orcid.org/0000-0001-5554-1582>

ORCID: Ahmed Y. Shash: <https://orcid.org/0000-0002-8135-4761>

ORCID: Mahmoud Abd Rabour: <https://orcid.org/0000-0002-5020-3231>

ORCID: El-Sherbiny: <https://orcid.org/0000-0003-4562-6616>

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