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Effect of welding on distortion changes in fillet joints with different sequences

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ABSTRACT

Gas Metal Arc Welding (GMAW) is widely used in fabrication due to its efficiency and weld quality. This study examined the influence of welding sequence on distortion in 316 stainless steel fillet joints using the GMAW-pulsed process. Two techniques—back-step welding and string welding—were applied without strongbacks on 50 mm × 50 mm × 5 mm specimens, with 3–5 seconds between passes. Distortion was measured using a trigonometric calculation based on displacement. Results show that back-step welding consistently reduced angular distortion compared to string welding. For vertical plates, back-step yielded 14.53°, 13.59°, and 14.30°, versus 15.42°, 14.07°, and 14.76° for string welding. For horizontal plates, values were –3.93 mm, 4.12 mm, and –6.20 mm for back-step, compared to –10.15 mm, 1.91 mm, and –8.20 mm for string welding. Reduced distortion is attributed to intermittent bead placement, which limits heat accumulation and residual stress. These findings highlight the importance of sequence selection in minimizing distortion, particularly in precision-demanding sectors such as marine and automotive fabrication, and support the inclusion of back-step welding in welder training programs.

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1. INTRODUCTION

Welding is widely used in fabrication for various applications, including shipbuilding, aircraft, automotive, and building structures (Chaudhary, 2017; Wang et al., 2025). In the welding process, several methods can be applied, such as gas tungsten arc welding (GTAW) (Bouhelal et al., 2025), shielded metal arc welding (SMAW) (Afzal et al., 2025), flux cored arc welding (FCAW) (Malhotra et al., 2022), and gas metal arc welding (GMAW) (Gandhi & Ghosh, 2025). Among these, the GMAW method is one of the most commonly used, especially in the manufacture of marine fabrication components such as vessels (Rubino et al., 2023). In the process, an electric arc serves as the heat source, melting the metal joint (Dadkhah et al., 2025; Kumar & Timothy, 2019). GMAW offers several advantages, including high weld toughness, concentrated arc, time efficiency, and relatively low distortion rate (Baskoro et al., 2019; Nishanth & Venkatesan, 2022).

Distortion —defined as deviation in the shape of the joined parts—often occurs in welding due to uneven heat absorption, which causes non-uniform expansion and contraction (Bintari Nurhayati et al., 2016; Chen et al., 2024; Seo & Lee, 2025). Distortion is closely linked to residual stress, which results from tensile and compressive forces generated by welding heat that are unevenly distributed (Ramadhan, 2017; Horváth et al., 2025; Mandal, 2017; Pujono et al., 2025). Residual stress can compromise dimensional accuracy and structural strength, often requiring corrective processes such as flame straightening, which increase production time and cost (Pangesti, 2016).

Distortion can be minimized through various strategies, including the use of strongbacks, heat input control, and adjustment of the welding sequence (Liang & Deng, 2018; Sun & Dilger, 2023). Welding sequence selection is particularly effective in reducing residual stress and distortion (Ozcatalbas & Vural, 2009). Two common sequences are the back-step and string welding technique. The difference in heat transfer characteristics between these methods significantly affects residual stress development and distortion. Back-step welding deposits short, discontinuous weld beads in the reverse direction of the overall progression, allowing partial cooling between passes (Jilabi, 2024). This intermittent heating lowers the peak temperature, reduces steep thermal gradients, and promotes uniform contraction (Liang & Deng, 2018). Consequently, tensile residual stresses are reduced, limiting angular distortion (Horváth et al., 2025). In contrast, string welding applies continuous heat along the weld path, producing higher thermal gradients and localized expansion, followed by uneven contraction (Malhotra et al., 2022; Sun & Dilger, 2023). Given that 316 stainless steel has low thermal conductivity and a high coefficient of thermal expansion (Mandal, 2017), it is especially sensitive to variations in heat input and cooling patterns, making welding sequence selection critical for distortion control.

This selection becomes even more crucial in constructions with tight dimensional tolerances, such as those in the marine and automotive industries, where small deviations can compromise component fit-up, alignment, and performance. These sectors often involve long, thin plates or complex assemblies that are highly susceptible to thermal deformation (Rubino et al., 2023; Sun & Dilger, 2023). In shipbuilding, for example, hull panels must align precisely to prevent hydrodynamic inefficiencies and structural weaknesses, while in automotive manufacturing, body panels and chassis components require accurate positioning to ensure safety, aerodynamics, and noise–vibration–harshness (NVH) control (Azad et al., 2020; Horváth et al., 2025). Incorrect sequence selection can lead to cumulative distortion exceeding allowable tolerances, resulting in costly rework or scrapping of parts. Therefore, controlling residual stresses and distortion through an optimized welding sequence is essential for maintaining dimensional accuracy, minimizing corrective work, and ensuring long-term performance in precision-demanding industries (Liang & Deng, 2018; Ozcatalbas & Vural, 2009).

Previous research supports the observations. (Jilabi, 2024) demonstrated that applying an optimized sequence in GTAW on butt joints reduced distortion by up to 38.64% compared to welding without sequence control. Similarly, (Azad et al., 2020) reported that the welding sequence significantly affects deformation in fillet joints using the GMAW process. Building on these findings, the present research investigates the effects of two welding sequences—back-step welding and string welding—on distortion in GMAW-pulsed fillet joints of 316 stainless steel, with the goal of improving performance and reducing fabrication costs.

2. RESEARCH METHOD

The experimental procedure followed the sequence illustrated in Figure 1, beginning with observation, preparation of materials and tools, parameter selection, distortion testing, and concluding with data analysis.

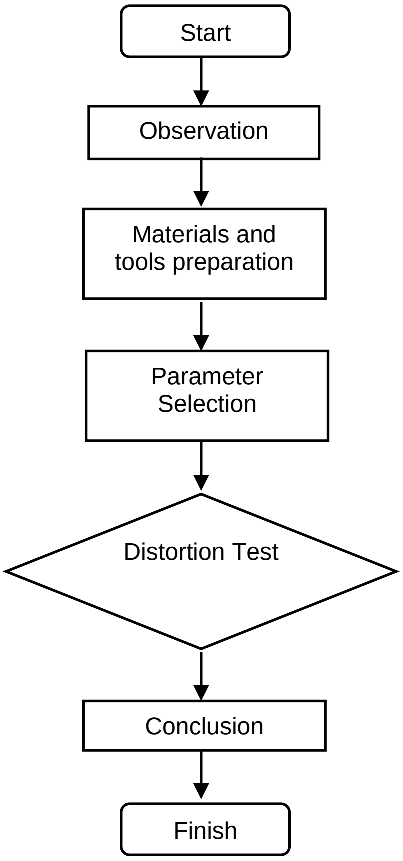
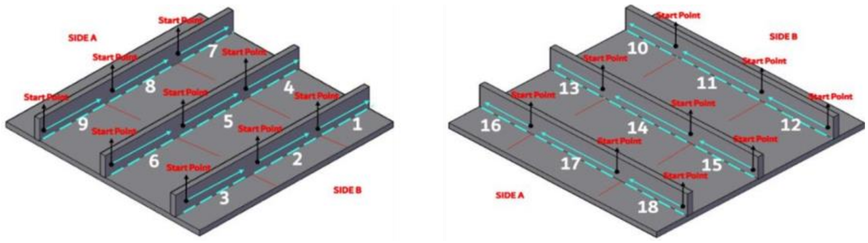


Figure 1. Flow chart

This study compared two welding sequence techniques—back-step welding and string welding—using the GMAW-pulsed process without the use of strongbacks. The workpiece material was 316 stainless steel, cut into plates measuring 50 mm × 50 mm × 5 mm. The filler material was ESAB ER316LSI wire, 1.2 mm in diameter. The welding equipment used was a GMAW-pulsed machine. Supporting tools included a caliper, grinder, measuring tape, cutting pliers, and wire brush. In the back-step welding technique, short adjacent weld beads were deposited in the reverse direction of the overall welding progression, with a 3–5 second pause between passes to allow partial cooling. In the string welding technique, the weld was made in a continuous straight path while maintaining a constant welding speed (Jilabi, 2018). The sequence patterns for each method are illustrated in Figures 2 and 3. After welding, distortion was measured at three vertical plates and three horizontal plates (highlighted with question marks) as indicated in Figure 4. Measurements were analyzed using the trigonometric formula:

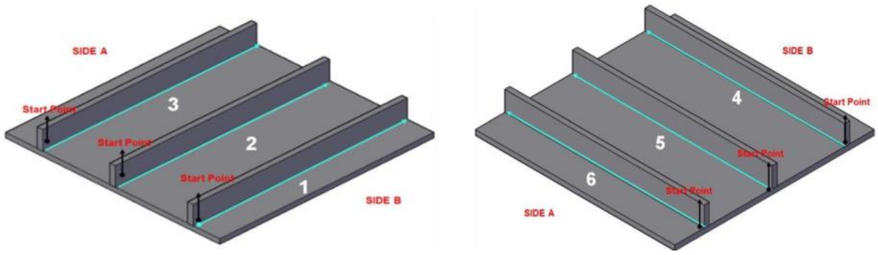
$$Cos\ A = \frac{x}{r} \qquad \text{.........(1)}$$

Where A is the angular distortion (degrees), x is the horizontal displacement or shrinkage (mm), and r is the radius or distance from the pivot point to the measurement location (mm). This method allowed accurate quantification of angular changes caused by thermal deformation.



(a) (b)

Figure 2. Back Step Welding Technique Process for (a) Side 1 and (b) Side 2



(a) (b)

Figure 3. String Welding Technique Process for (a) Side 1 and (b) Side 2

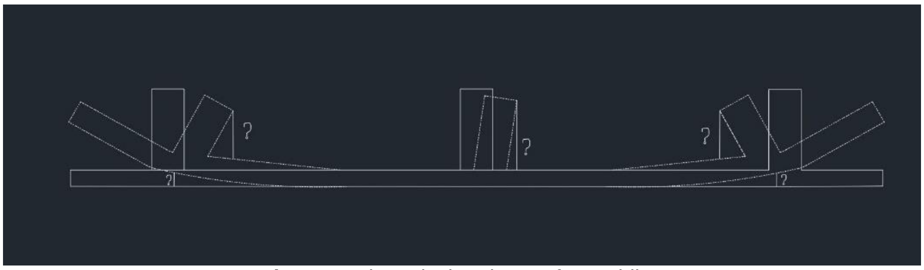


Figure 4. The calculated part after welding

3. RESULTS AND DISCUSSIONS

Figures 5 and 6 show the welded specimens produced using the back-step and string welding sequences, respectively. Distortion measurements were taken on vertical plates 1, 2, and 3, as well as horizontal plates 1, 2, and 3. Tables 1 and 2 summarize the distortion values for both sequences.

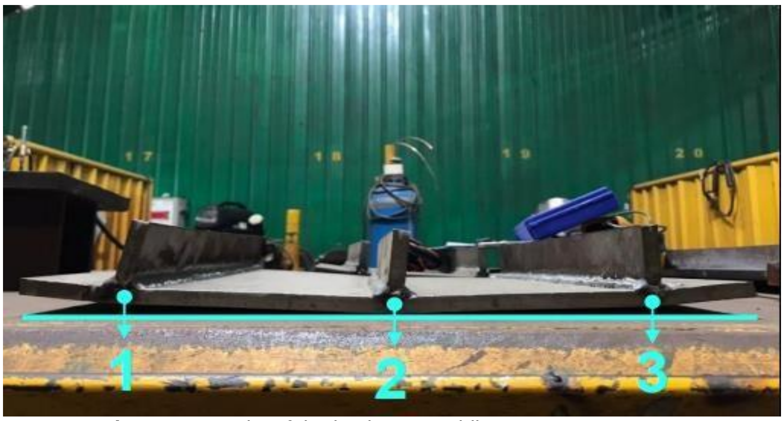


Figure 5. Results of the back-step welding sequence process

Figure 6. Results of the string welding sequence process

For vertical plate 1, the back-step method resulted in a distortion of 14.53°, compared to 15.42° for string welding. Vertical plate 2 showed 13.59° for back-step versus 14.07° for string welding, and vertical plate 3 showed 14.30° for back-step versus 14.76° for string welding. In the horizontal direction, back-step welding produced values of –3.93 mm, 4.12 mm, and –6.20 mm for plates 1, 2, and 3, respectively, whereas string welding produced –10.15 mm, 1.91 mm, and –8.20 mm. These results confirm that back-step welding is more effective in minimizing both vertical and horizontal distortion. The reduced distortion is attributed to the intermittent deposition pattern, which decreases shrinkage forces and limits stress accumulation by allowing partial cooling between passes (Jilabi, 2024).

Table 1. Back-step welding sequence calculation results

Name	Before Welding (mm)	After Welding (mm)	Distortion
Vertical Plate 1	50.26	48.70	14.53°
Vertical Plate 2	50.23	48.83	13.59°
Vertical Plate 3	50.26	48.74	14.30°
Horizontal Plate 1	2.75	6.68	-3.93 mm
Horizontal Plate 2	4.12	0.00	4.12 mm
Horizontal Plate 3	3.68	10.06	-6.20 mm

Table 2. String welding sequence calculation results

Name	Before Welding (mm)	After Welding (mm)	Distortion
Vertical Plate 1	50.28	48.50	15.42°
Vertical Plate 2	50.23	48.76	14.07°
Vertical Plate 3	50.25	48.65	14.76°
Horizontal Plate 1	0.00	10.15	-10.15 mm
Horizontal Plate 2	1.91	0.00	1.91 mm
Horizontal Plate 3	1.00	9.20	-8.20 mm

The differences in vertical and horizontal distortion between the two sequences have direct implications for joint performance and longevity. Higher vertical distortion, as observed in string welding, increases residual stresses and creates stress concentration zones at the weld toe, reducing fatigue life and load-bearing capacity (Chen et al., 2024; Mandal, 2017). Excessive horizontal displacement can compromise dimensional accuracy, leading to misalignments that require corrective work and may degrade material properties (Azad et al., 2020; Sun & Dilger, 2023). In contrast, the lower distortion achieved with back-step welding promotes uniform stress distribution, better dimensional fit-up, and improved structural integrity (Jilabi, 2024; Liang & Deng, 2018)

When applied to large structures such as ship panels or plate girders, scale alters heat-sink behaviour and restraint conditions, potentially changing distortion modes from angular bending to more complex buckling. To translate these findings to a production scale, strategies such as calibrated FEM simulations, localized low-heat deposition, balanced welding sequences, and appropriate fixturing or strongbacks should be implemented. Large-scale welding should also include validation of residual-stress fields and buckling limits to ensure both distortion control and structural performance (Chen et al., 2024; Seo & Lee, 2025)

4. CONCLUSION

This study investigated the effect of welding sequence—back-step and string welding—on distortion in the GMAW-pulsed process applied to 316 stainless steel fillet joints. The results showed that back-step welding produced smaller distortions in vertical plates 1 (14.53°), 2 (13.59°), and 3 (14.30°) compared to string welding, which yielded 15.42°, 14.07°, and 14.76°, respectively. Horizontal plate measurements also indicated lower distortion with the back-step method: plate 1 (-3.93 mm), plate 2 (4.12 mm), and plate 3 (-6.02 mm), versus string welding values of -10.15 mm, 1.91 mm, and -8.20 mm. These findings confirm that distortion can be minimized by selecting an appropriate welding sequence.

The results of this research can also inform welder training programs to encourage broader adoption of the back-step method in industry. Training should combine distortion-control principles with practical demonstrations comparing back-step and string welding, supported by hands-on and simulation-based exercises to illustrate how bead placement and cooling intervals reduce residual stress. Including the technique in certification requirements and shop-floor guidelines will promote consistent application, particularly in sectors where precision and distortion control are critical, such as marine and automotive fabrication. Furthermore, distortion control can be enhanced by integrating appropriate sequence settings with additional measures: controlling heat input (reduced current, higher travel speed, smaller beads), limiting interpass temperature, and applying preheat or controlled cooling. Mechanical aids such as strongbacks, clamps, chill bars, and balanced or skip-sequencing help restrain shrinkage and distribute stresses.

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