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Microstructure, distortion and residual stress investigation in a bio-inspired welding pattern

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Abstract

In Nature, when two surfaces are bonded, the joining interface usually follows a structurally optimized non-linear pattern, like cranial sutures. This distinctive characteristic of Nature could be imitated when joining thin plates by laser welding using a 'zig-zag' path. It is expected that both welding stress and strain will develop in a different way as compared to the conventional butt-welding straight path due to a different heat flow and stiffness the weld bead undergoes during the welding process. To assess the resulting residual stress and distortion, as a function of the laser welding path, experimental investigations were carried out by X-ray diffraction technique and Coordinate Measurement Machine (CMM Hybrid), respectively. Results showed that the studied bio-inspired welding pattern can effectively alter both residual stresses and distortions. The outcome of this study unveils the potential of such a welding strategy to reduce the magnitude of detrimental tensile residual stress, opening new avenues to the development of more structurally efficient weldments as compared to standard linear welding.

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1. Introduction

The main challenge in welding research field is to find new strategies to improve the metallurgical and mechanical performances of welded joints. Up to now, all those approaches mainly focused on the welding process itself. Consequently, we have been experiencing a gradual shift from arc welding techniques to high-power density welding methods (such as laser or electron beam welding). This development has allowed for a significant reduction of the fusion zone (FZ) and heat affected zone (HAZ) which are the weakest structural points of a welded structure, i.e., crack nucleation site (Murua et al. 2024). From a metallurgical point of view, however, the as-welded joint may not have the most effective microstructure concerning its corrosion resistance and mechanical properties, so corrective measures may be necessary to control the microstructure through pre- or post-heating or even post-welding heat treatments (Ferro et al. 2008; Angella et al., 2017; Barbieri et al., 2024). Moreover, welded joints, in as-welded conditions, are affected by both thermal and residual stresses that in the first case may promote hot cracking (Zhang et al., 2012; Jing et al., 2025; Coniglio et al., 2020; Hu and Richardson, 2006; Norouzian et al., 2023) and, in the second case, may reduce their fatigue strength at high fatigue cycle (Ferro, 2014; Ferro and Berto, 2016; Ferro et al., 2017; Salvati, 2024) or compromise the assembly operations because of residual distortions (Romanin et al., 2021).

A small step forward in improving the performance of welded joints has been made with the development of solid or semi-solid-state welds such as friction stir welding (FSW) (Kilic et al., 2023; Christy et al., 2021) and the more recent hybrid metal extrusion and bonding (HYB) technology (Blindheim et al. 2018; Sandnes et al., 2019; Aakenes et al. 2014). Nevertheless, in FSW the HAZ remains the weakest region of the welded structure, even though some improvements were obtained in that direction with HYB.

To the best of the author's knowledge, no tentative has been done yet in exploring the effect of the welding path on the metallurgical and mechanical properties of welded joints. In this regard, some sources of inspiration can be taken from Nature, which rarely sees a straight joining path between two surfaces. More commonly, it is observed that Nature follows the interlocking paradigm, as in cranial (ref to Fig.1a) or red-bellied woodpecker (Melanerpes carolinus) beak sutures (ref to Fig.1b). Despite the bio-inspired suture joints have been studied and reported in the literature (Li et al. 2012; Li et al. 2013; Lin et al., 2014a; Lin et al., 2014b), the potentialities of bio-inspired welding path have not been explored yet, except for a preliminary numerical investigation carried out by the authors (Ferro et al., 2024).

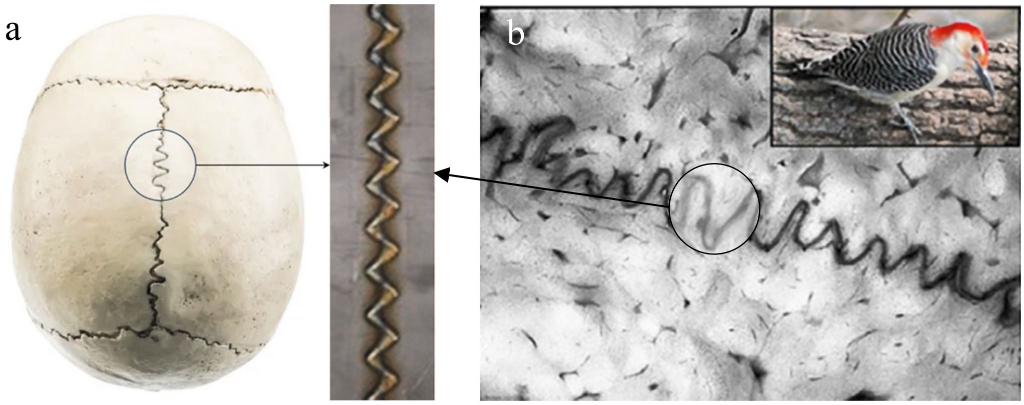

Fig. 1 – Laser welding path mimicking Nature: a) cranial suture; b) red-bellied woodpecker (Melanerpes carolinus) beak suture (adapted from Lee et al., 2014),

Improved static and mechanical strength of the welded joint are amongst the main expected advantages of bio-inspired welding patterns. Additionally, it is expected to obtain different residual stress distributions promoted by different thermo-mechanical conditions experienced by the joints during the welding process, as compared with a traditional linear welding path. The weldability of some difficult-to-weld alloys could also be improved by the exploitation of the sought welding strategy by reducing solidification cracking tendency, by limiting the amount of brittle phases in HAZ and by obtaining a more balanced microstructure for instance in duplex stainless steels laser welded joints.

As mentioned above, in a recent work (Ferro et al. 2024), some numerical investigations were carried out to study the influence of a bio-inspired welding path on residual stress (RS) distribution with encouraging results. The key aim of the present study is to assess such residual stresses by X-ray diffraction technique and compare them with those coming from a standard straight-path laser butt-welded joint. Experimental results confirm the possibility of tuning welding-induced RS distribution with a significant reduction mainly in the longitudinal direction compared with standard linear path welding. Furthermore, to complement the analysis, microstructural observations, hardness evaluation and distortion evaluation are conducted and discussed.

2. Materials and Methods

2 mm thick, 100 mm wide and 300 mm long sheets of AISI 304 steel, the composition of which is shown in table 1, were butt welded using a laser source. The welding parameters used are summarized in table 2. The edges of the plates undergoing welding were prepared by water jet cutting.

Table 1. Chemical composition (wt%) (data obtained with UV Master Foundry Quantum Meter).

C	Mn	P	S	Si	Cr	Ni	Bal.
0.07	2.00	0.045	0.015	1.00	17.0-20.0	8.0-11.0	N ≤ 0.11

Table 2. Laser welding parameters.

Welding speed (mm/min)	Spot (mm)	Constraints	Laser power (W)	Focus (mm)	Gas	gas flow rate (l/min)
600	0.27	Table with rulers	600	+3	Nitrogen	20

Two different welding paths (WP) were used, the straight or standard path (used as control/reference) and the 'Zig-Zag' path - geometrical shape and dimensions are shown in Fig. 2.

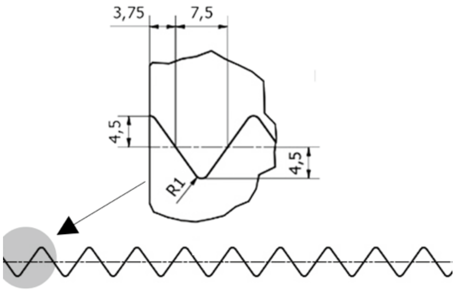

Fig. 2 – Zig-Zag' welding path and details about its geometrical parameters [mm].

The residual stress was experimentally evaluated by laboratory X-ray diffraction method along both the transverse direction (σ_{xx}) and longitudinal direction (σ_{yy}) with respect to the weld line as shown in Fig. 3. Details about the evaluations are collected in Table 3

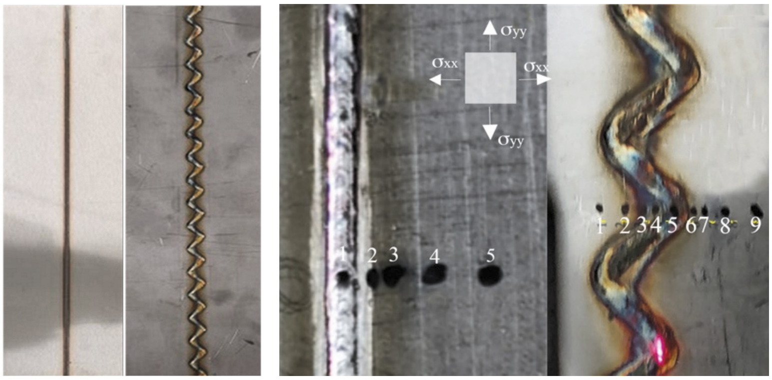

Fig. 3 – Welding paths overview and detail about the position of points where residual stresses were evaluated.

Table 3. X-ray diffraction measurement parameters.

X-ray device	GNR Spider X
Radiation	Cr-Kα with Vanadium filter, penetration depth 15 μm
Collimator size	0.5 mm
Method	*Centroid*
Acquisition time	300 s/ψ angle
ψ − angles	11 ψ-angles, $-30° < \psi < 30°$
Elastic constants	$E = 220$ GPa, $\nu = 0.34$

A Coordinate Measurement Machine (CMM Hybrid) was used with both optical and tactile probe systems to measure the deformation of two samples in both the standard linear and bio-inspired configurations. Evaluation points were collected in a linear pattern fashion using a spatial spacing of 1 mm. The probe's movement speed was approximately 5 millimeters per second, ensuring efficient data collection for a comprehensive analysis of changes. Subsequently, the collected data were processed using MATLAB software to generate images as shown in Fig. 9.

Finally, standard metallographic analysis and microhardness profiles over the weld bead cross section were performed to characterize the joints.

3. Results and discussion

3.1. Microstructure and microhardness profiles

Figure 4 shows a macrograph of the cross-section of the bead and its position with respect to the welding line for both the considered welding configurations. It can be clearly observed that the welding bead of the zig-zag configuration is considerably wider in the section corresponding to the crest of the ‘zig-zag’ path, as compared with the linear counterpart.

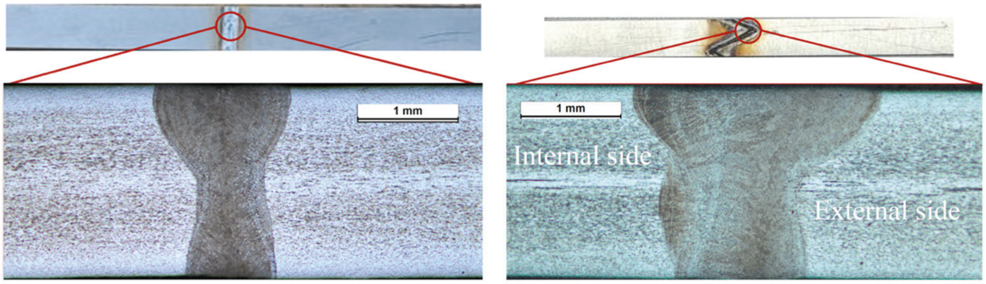

Fig. 4 – Macrographs of the welds.

For the sake of simplicity only the microstructure of the ‘zig-zag’ welding is reported in Fig. 5 since no differences were detected (with the exception of a slightly variation in grain dimension at the zone very close to the ZF/HAZ interface).

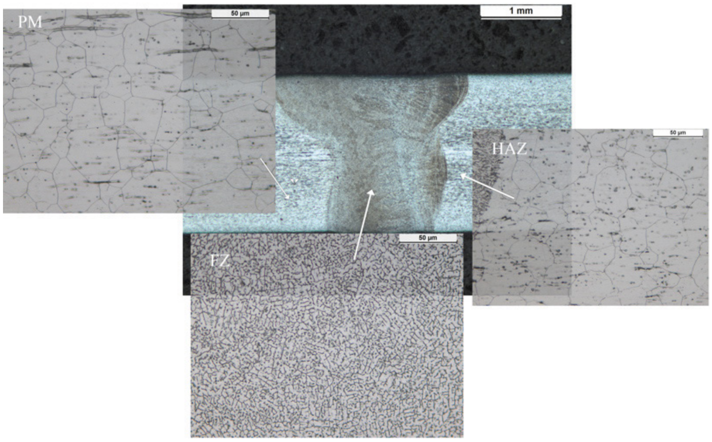

Fig. 5 – Micrographs of parent metal, fusion and heat-affected zone.

The fusion zone (FZ) is characterized by a very fine dendritic microstructure, induced by the high cooling rate, typical of laser welding. On the other hand, both parent material and heat-affected zone show an equiaxed microstructure having a mean grain size dimension of about 22÷25 µm.

Microhardness profiles (Fig. 6), evaluated on the cross-sections shown in Fig. 4, reveal some slight differences both in FZ and on the right side of the welding line corresponding to the internal side of the ‘zig-zag’ welding (Fig. 4).

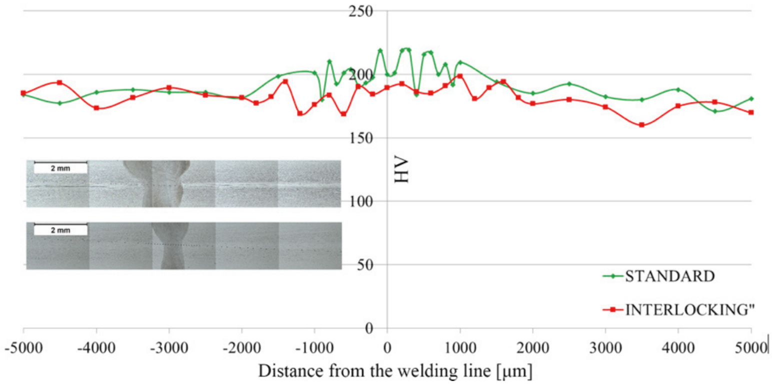

Fig. 6 – Microhardness profiles.

Both microstructure and microhardness profiles show that the ‘zig-zag’ welding undergoes a different thermal history compared to standard welding. By referring to Fig. 7, when the laser source is at point A, the heat flux pre-heats zone B, and vice versa, when the laser source is at point B, the heat flux post-heats zone A. This effect induces an asymmetrical microhardness profile with the internal side of the ‘zig-zag’ welding slightly weaker, due to the heat ‘accumulated’ in that zone compared to the external side.

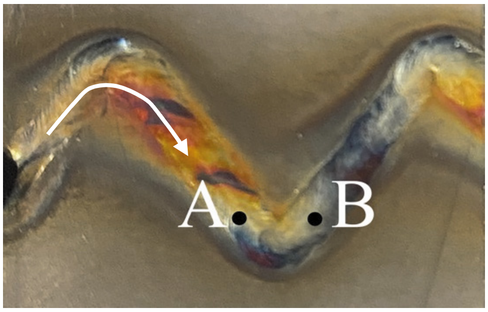

Fig. 7 – ‘Zig-zag’ welding with point A and point B undergoing post and pre heating.

3.2. Residual stresses

RS values as a function of the distance from the weld line are shown in Fig. 8. RS distributions of the ‘zig-zag’ welding are asymmetric with the internal side (left side in fig. 8) showing lower values as compared to the external side. The longitudinal RS component results, in almost the entire path, are significantly lower than that resulting from the standard welding (Fig. 8b). On the opposite, transverse RS induced by the ‘zig-zag’ welding appears significantly higher compared to the reference one, but only in the HAZ and external side (Fig. 8a). While the RS of the linear weld agrees with the results reported in the literature, i.e. longitudinal RS being higher than transverse RS (Lu et al., 2020), the zig-zag pattern presents an unconventional trend.

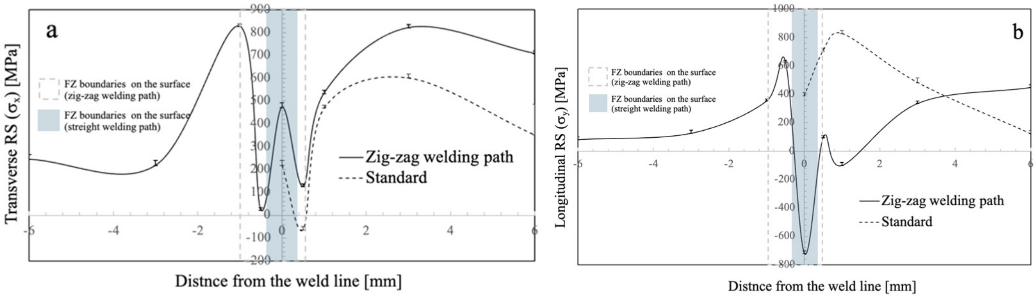

Fig. 8 – Residual stress distribution along the paths shown in Fig. 3: a) transversal RS (σ_x); b) longitudinal RS (σ_y)

RS results from a complex interaction between clamping conditions and thermal stress gradients, which can rationally explain different results obtained in the case of ‘zig-zag’ welding with respect to the linear counterpart. Indeed, due to the wider overall region undergoing welding for the zig-zag condition, the inner area of the welding undergoes a sort of ‘heat accumulation’ as compared to the external side where heat is dissipated more rapidly. For this reason, it is expected that the inner region of the welding experiences lower temperature gradients and therefore lower thermal stress. About the geometrical effect, it is reasonable to think that along the longitudinal direction, the restraint given by the parent material (PM) is lower than that induced by the PM in the standard welding. This results in an overall reduction of the longitudinal residual stress component in the ‘zig-zag’ welding compared to what occurs in the straight path welding.

Figure 9 shows the distortion pattern induced by standard (Fig. 9a) and ‘zig-zag’ (Fig. 9b) welding pattern. The distortion of the cross-section 50 mm from the symmetry plane (coincident with the welding line in the standard welding) is shown, as well.

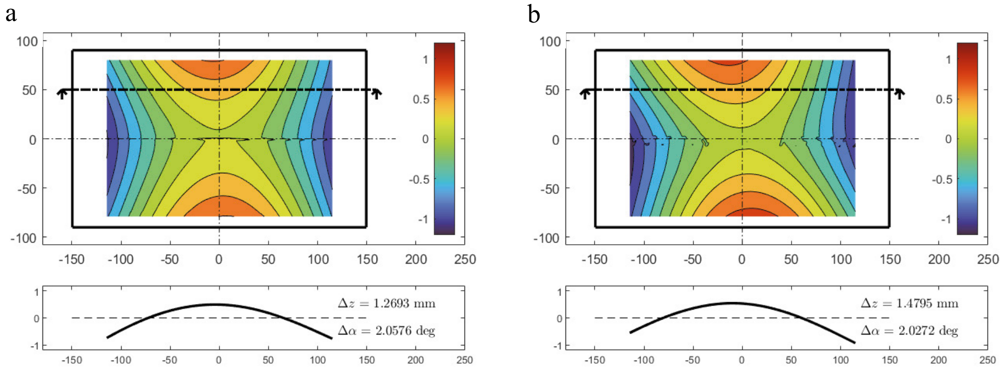

Fig. 9 – Distortion pattern [mm] induced by standard (a) and ‘zig-zag’ (b) welding path.

It is observed that the ‘zig-zag’ welding pattern slightly increases the plate distortion (Δz) compared to the standard welding path.

Finally, it is supposed that the differences in residual distortions and stress values between the two welding paths are strongly dependent on the ‘zig-zag’ parameters and future research should investigate such geometry effect.

4. Conclusions

The study experimentally explored, for the first time (to the best of the author's knowledge), the significant changes in terms of residual stress induced by the bio-inspired welding pattern. This opens new avenues to tune residual stresses and distortion of laser butt-welded joints by carefully optimizing the shape of the welding path and possibly the welding processing parameter as well. The main outcomes of the research can be summarized as follows:

1. Using a bio-inspired welding path it is possible to modify the residual stress distribution compared to standard welding with a positive reduction of their values above all in the longitudinal direction.
2. This effect is due to a significantly different thermal history of the bead induced by the zig-zag welding path and by a dissimilar local constriction induced by the parent metal to the fusion zone during its solidification and cooling.
3. The zig-zag welding path slightly increases the plate distortion compared to the standard welding path.
4. It is supposed that the differences in residual distortion and stress values between the two welding paths are strongly dependent on the 'zig-zag' geometry parameters and future research should investigate such geometry effect.

This pioneering bio-inspired approach to butt welding showed interesting results that merit being deeply explored, not only in terms of residual stress and distortion but, also for what concerns its static and fatigue strength. Many processing parameters are yet to be explored, from the shape of the path to the individual geometric parameters such as amplitude and period, in relation also to the process parameters.

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