Visual Abstract

Asymptotic response of friction stir welded joint under cyclic loading

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ABSTRACT. Fatigue takes a place more and more important in the design of structures, it remains a key point in the mechanical dimensioning of structures. The Friction Stir Welding (FSW) process is regarded today as the most promising alternative to traditional joining methods. It ranks among the most recent assembly processes and is considered a new technique for the 21st century. Indeed, if the FSW welding process has several advantages, it introduces very strong microstructure heterogeneities in the welded joints.
This leads to heterogeneous mechanical behavior in each of the constituent zones. some important efforts have been deployed in industry as well as in research laboratories to understand the behavior of welded joints by the FSW process. There are many questions about the behavior of these areas.
This study led to the characterization and understanding of the fatigue behavior of a 2024-T351 structure welded by the FSW process. It presents in a numerical work which aims to help determine the asymptotic response of each zone constituting the 2024-T351 joint welded by FSW subjected to a cyclic loading and to fully understand the behavior of these zones.
To carry out an analysis and a simulation under cyclic loading, our choice fell on the use of the direct cyclic method. Numerical simulation of crack propagation was performed using the extended finite element method (XFEM).
This research consists in the implementation of the XFEM in fatigue in a multiscale model XFEM / direct cyclic.
The numerical results consist in highlighting the heterogeneities in the mechanical behavior of the welded joint and in evaluating the impact of the FSW process on the failure of these FSW zones.

KEYWORDS. Direct Cyclic; FSW; XFEM; Fatigue; Asymptotic response.

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INTRODUCTION

Friction stir welding (FSW) is a new solid-state welding, method developed by TWI in the 1990s, offering several advantages over conventional welding methods [1, 2] FSW uses a rotating and traversing non consumable tool to generate frictional heat and cause mechanical deformation at the joint [4].

Friction stir welding uses the principle of convection of mechanical energy, produced by the pressure and rotation of the tool, into thermal energy by friction of the latter with the parts to be assembled. The heat generated generates localized transformations where the material changes from an elasto-viscoplastic behaviour with high mechanical resistance to a viscoplastic behavior with low resistance, favoring the formation of the junction [22]. The FSW process, shown schematically in Fig..1, During the welding process, heat is generated due to the friction between the tool and the workpiece, as well as due to the severe plastic deformation of the material [5].

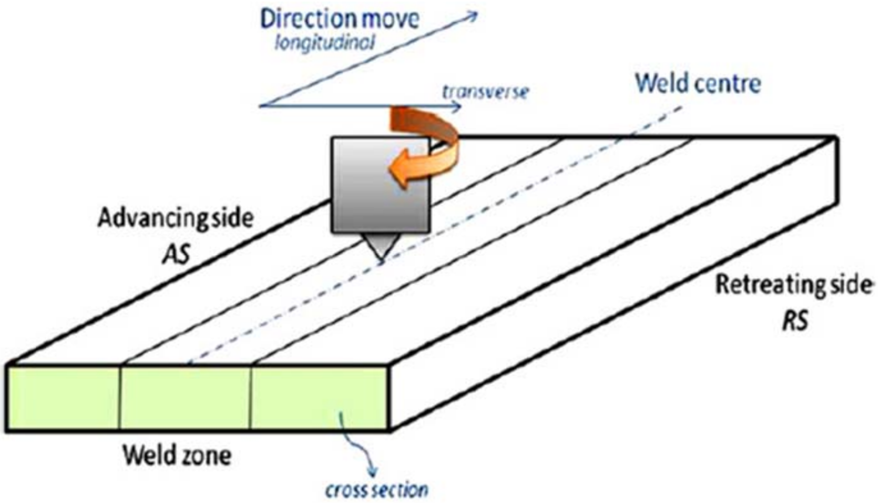

Figure 1: Geometry of FSW process, also indicating the tool transverse direction [6].

A welded joint is made only from the base metals of the assembled parts and does not require any filler metal [4].
The weld created by this process is not symmetrical about the parting line. The side where the two velocity vectors (translation and rotation) are in the same direction is called "advancing side" (AS). The one where these two vectors are opposite is called a "retreating side" (RS) (Fig. 1) [2].
During welding, a thermal and mechanical gradient is introduced, leading to a microstructure gradient within and around the weld [1]. The FSW community unanimously agrees on the number and naming of the macroscopic areas that make up the FSW welded joint. In general, the welded joint has four zones: the core, the thermomechanically affected zone (ZATM), the thermally affected zone (ZAT) and the base metal (MB). So the FSW welding has a very heterogeneous microstructure along the joint, the shape of the bead, the grain size and the size of the areas constituting the joint (Fig.2).

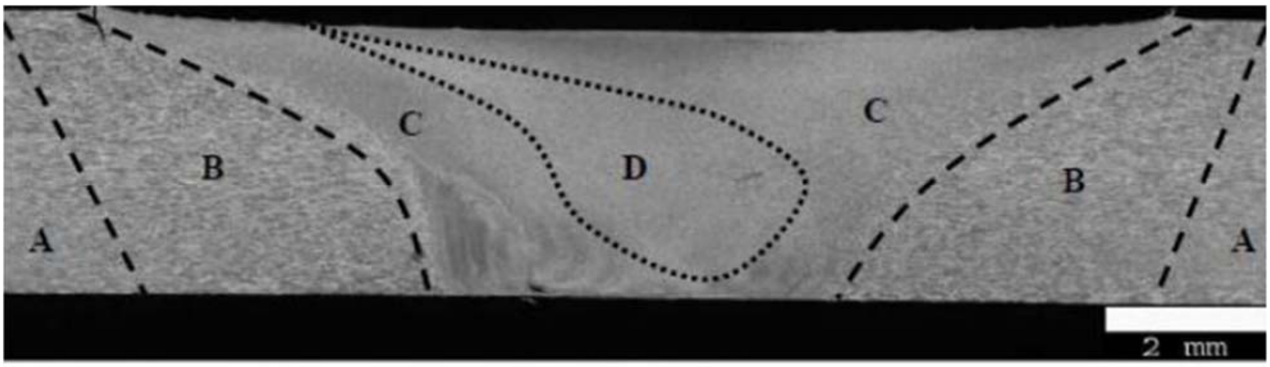

Figure 2: Macrographic section of a weld bead from AA7020 showing four distinct areas: (A) base metal, (B) heat affected area, (C) thermo-mechanically affected area and (D) nugget.

These heterogeneities introduced by FSW welding make it difficult to study the mechanical behavior of these joints this study constitutes an element of response and of the comprehension of the behavior of the joint 2024-T351 welded by FSW aiming at the numerical development of this joint and the implementation of the method of the extended finite elements (XFEM) in cyclic loading.

For broadening and improve understanding the joints FSW, it is necessary to clarify the local fatigue behaviour of different areas of the FSW joints. The fatigue crack propagation of FSW is known to be concerned by the both microstructures around the welded zone [3].

NUMERICAL APPROACH AND DEVELOPED MODEL

Despite a good number of publications on the FSW process, the characterization and numerical analysis of the harmfulness of the defects in the different areas of these joints remains limited.

This work is in addition to the various research studies that deal with the mechanical behavior of aluminum alloys welded by the FSW process and strongly contributes to numerically understanding the local fatigue behavior of the 2024-T351 joint.

The XFEM method has been used in order to successfully simulate the phenomenon of crack propagation in friction stir welded joint, without forgetting to take into account the plasticity at the crack tip, and to perform analysis and simulation under cyclic loading, we chose to use the direct cyclic method.

So therefore our work consists in the establishment of the XFEM in fatigue in a multi-scale model XFEM / Direct cyclic. The model coupled will be the most powerful and efficient tool for solving various problems in the fatigue behavior.

The XFEM was introduced by Moës and al. in 1999. The idea of XFEM consists in enriching the basis of the classical finite element method by a step function along the crack line to take into consideration the discontinuity of the displacement field across the crack and by some non-smooth functions representing the asymptotic displacement around the crack tip. The latter enrichment is the so-called singular enrichment [7], It allows enables automatic mesh generation with each new step of the crack growth [8, 9].

Till now XFEM has been most widely applied in solving crack problems, including fatigue crack propagation, and three-dimensional crack propagation, XFEM has also been implemented to solve plasticity problems [10]. Many works have been achieved in order to explore the capabilities of the XFEM and improve its accuracy as in [7, 9, 10, 11, 16, 17, 18, 19, 20, 21].

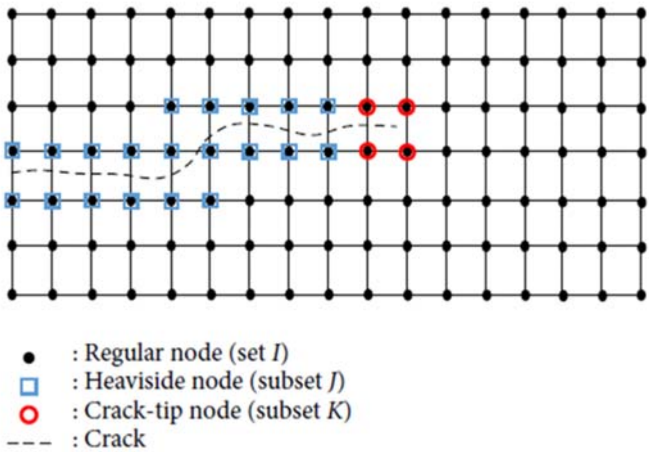

Figure 3: 2D finite element mesh of a cracked body [11].

PRESENTATION OF THE DIRECT CYCLIC METHOD

The study and the numerical characterization of the mechanical behavior of a structure is based on the determination of the stabilized response of the structure subjected to cyclic loading. However, this asymptotic response remains difficult to determine by conventional simulation techniques, in particular because of the necessary computation times.

It then makes it possible to construct the mechanical response of the studied structure, loading increment by loading increment, then cycle after cycle until a possible stabilized cycle. At each increment, the calculation codes generally use an iterative scheme of the Newton-Raphson type to construct the solution of the problem [15].

An iteration of the direct cyclic method includes 4 stages main:

- The global step: which makes it possible to search the kinematically and statically admissible fields at all times of the cycle by supposing known the field of plastic strains and internal variables at all times of the cycle.
- The local step: which allows, from the solutions of the global step, to search for fields that verify the law of behavior.
- The periodicity of the solutions which is imposed by a reinitialization of the plastic strains and the internal variables at the beginning of the cycle from the values obtained at the end of the cycle.
- The convergence condition which makes it possible to stop the iterative process checks the periodicity of the plastic strain fields and the internal variables at the end of the local step as well as the static admissibility of the stresses at the end of the local step.

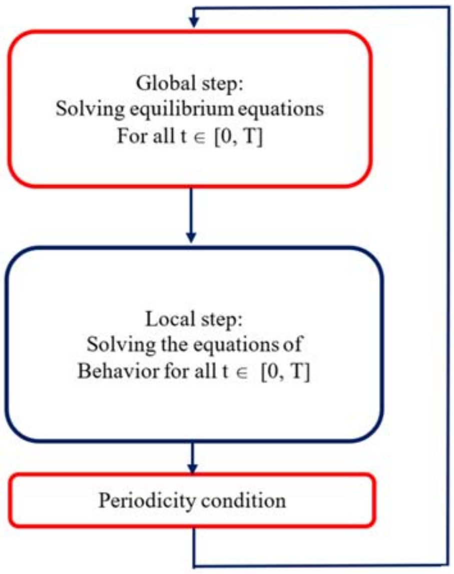

Figure 4: General principle of the direct cyclic method [12].

APPLICATION OF THE METHOD TO THE CALCULATIONS OF JOINT FSW 2024-T351

Four distinct materials are defined for the different zones ; Base Material (MB) - Heat Affected Zone (HAZ) -Thermo-Mechanically Affected Zone (TMAZ) and Nugget (N) within the developed model, so the constants are taken as follows:

Elastic party ; the mechanical properties of the welded joint 2024 T351 have been determined, the young's modulus and the Poisson's ratio are the same for all the zones, the hardening modulus and the exponent (n) vary along the welding zones (Tab. 1).

Elasto plastic ; stresses-strains have been described for all zones (Tab. 2), and without forgetting we take into account the mixing temperature of 2024-T351 T = 550 ° C [23].

FSW regimes	NZ	TMAZ	HAZ	PZ
Young's modulus (GPa)	68	68	68	68
Poisson's ratio	0.33	0.33	0.33	0.33
Yield stress (MPa)	350	272	448	370
Hardening constant	-	800	719	770
Hardening exponent	-	0.1266	0.05546	0.086
Hardness (Hv1)	142	118	167	132
Residual stress (MPa)	-41	95	-20	0

Table 1: Material properties of FSW zones [14].

PZ		HAZ		TMAZ		NZ	
Strain	Stress	Strain	Stress	Strain	Stress	Strain	Stress
0.0003	20	0.0004	25	0.0007	50.34	0.00044	30.43
0.0006	40	0.0006	35	0.00123	75.86	0.0008	51.30
0.0009	45	0.0010	58	0.0016	106.9	0.0012	69.56
0.0014	90	0.00126	83	0.0020	131.03	0.0015	91.30
0.0021	125	0.0015	95	0.0031	186.21	0.0021	130.43
0.0034	220	0.0020	130	0.0045	268.96	0.0032	186.95
0.0050	300	0.0028	175	0.0057	331.03	0.0043	286.96
0.0058	320	0.00438	280			0.0055	331.91
0.0084	440	0.00558	330				
0.0120	487	0.00898	480				
		0.01166	540				

Table 2: Stress-strain data of FSW zones [14].

So, we formed numerically all the zones constituting the joint FSW 2024-T351 with the properties of each one ..., the model is already developed previously in our article [13] which treated a calculation XFEM under monotonic loading to determine the parameters of cracking of the joint 2024-T351.
In this work we wanted to highlight this approach on the same model in the cyclic regime, the same approach was adapted but with the cyclic numerical tests in order to achieve the asymptotic response of each zone in the welded joint 2024-T351.

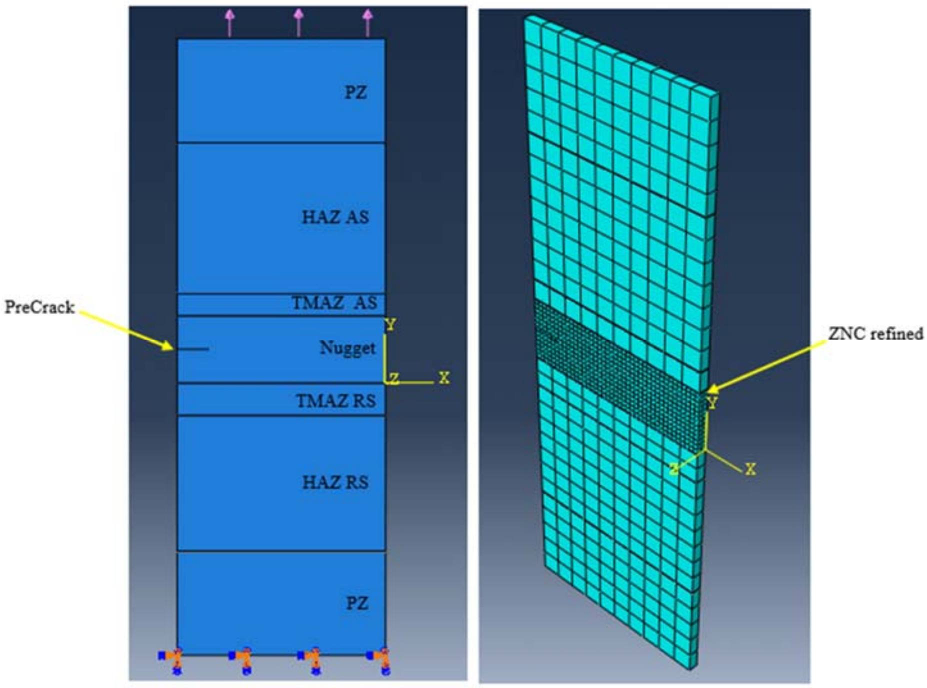

Figure 5: The model developed a) Geometry of the analyzed structure; b) Mesh of joint 2024-T351 [13].

The model FSW welded joint 3D using the calculation code by FE ABAQUS, developed on a rectangular thin plate pre-cracked (a_0 = 3mm) dimensions 60x20x1mm, so we choose a structured mesh (hexahedron) with volume elements at 8 (C3D8R) nodes without forgetting to finely mesh the cracked zone, of course the results are much more precise if the mesh of the the cracked area is finer.
Elasto-plastic crack-tip behavior must be written in order to take into account plasticity-induced loading history effects.
Using the direct cyclic method, the stress-strain curves in each zone were determined.

Fatigue tests in traction-traction were simulated in Abaqus / Standard under sinusoidal cyclic loading with imposed stress (Fig. 4). The maximum load applied to the specimen is 1kN, the load ratio is $R = F_{min} / F_{max} = 0.1$ and the stress frequency is 20 Hz. Fig. 5 illustrates the periodic amplitude imposed on ABAQUS.

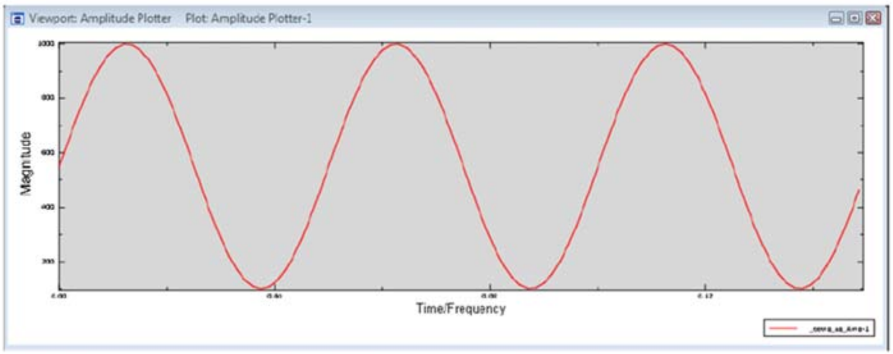

Figure 6: Amplitude applied during the fatigue test.

STABILIZATION ANALYSIS AND NUMERICAL ILLUSTRATIONS (ASYMPTOTIC BEHAVIOR OF THE DIFFERENT ZONES)

Fig. 6 illustrates the strain stress cycles (σ_{22} as a function of ε_{22}) at the nugget of the welded joint during a cyclic numerical test. The plot represents an element located very close to the crack point, which is why we see that the stress state changes from traction to compression during cycle depending on external loading.
Part (a) of the curve corresponds to the time required for the calculation code to reach the set point of the imposed loading. The calculation code requires one cycle (an average of 265 iterations) to perfectly reach the setpoint.
It is important to specify that for the simulated tests, the size of the time steps, size increments are 9.434e-4 for each cycle (T = 0.05) and the average number of iterations is at least 5, therefore the calculation code repeats each iteration 53 times to complete the calculation and ensure satisfactory precision of the solution. Over the course of iterations, the solution is corrected until convergence.
It is noted that the cyclic mechanical behavior of the nugget of the welded joint in alloy 2024-T351 around the crack point has a ratchet effect (part b of the curve); strong variations of the variables of the model are observed, in particular with incipient plasticity.
Once the plastic field is well established the variations between the cycles are less important and the evolution of the internal variables tend towards a periodic state over a certain number of cycles, this is the accommodation. (Part c of the curve) up to about 90% of total life.
We note that the stabilization is very slow, the evolution of the stress-strain cycles during the iterations shows that we obtain a good approximation of the solution from 120 iterations with 50 Fourier terms as indicated in Fig. 7. The shape of the cycle is well represented, while the level of average deformations of the solution remains slightly estimated.

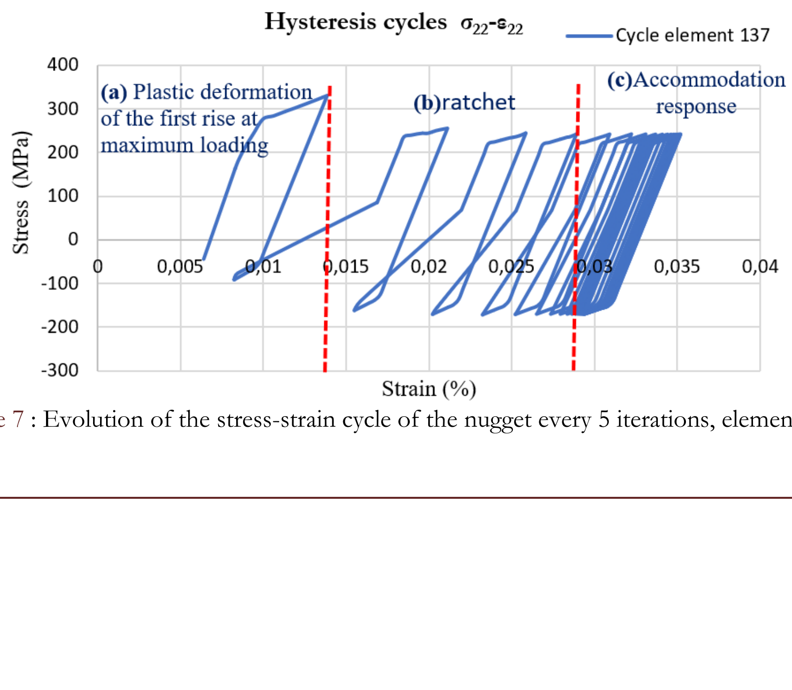

Figure 7 : Evolution of the stress-strain cycle of the nugget every 5 iterations, element 137.

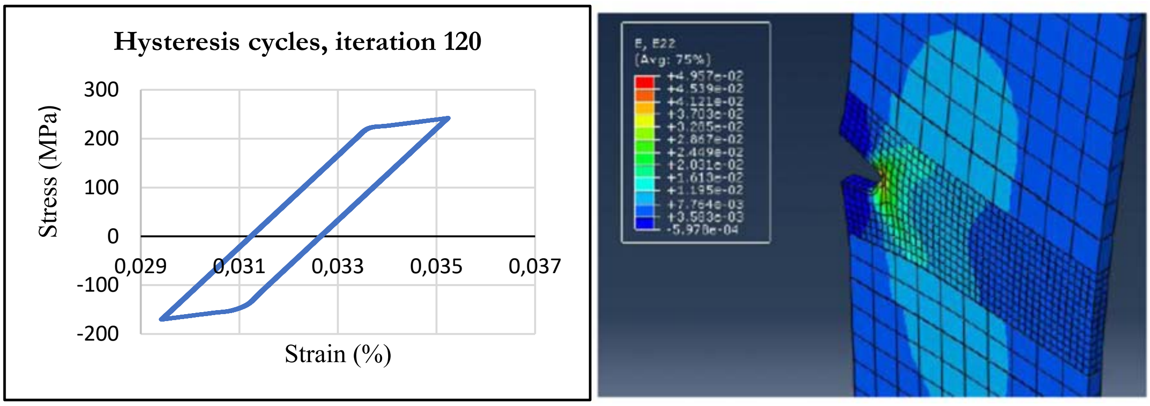

Figure 8: a) Stress-strain cycle obtained by DCM after 120 iterations. B) Deformation fields at the end of the cycle stabilized by DCM.

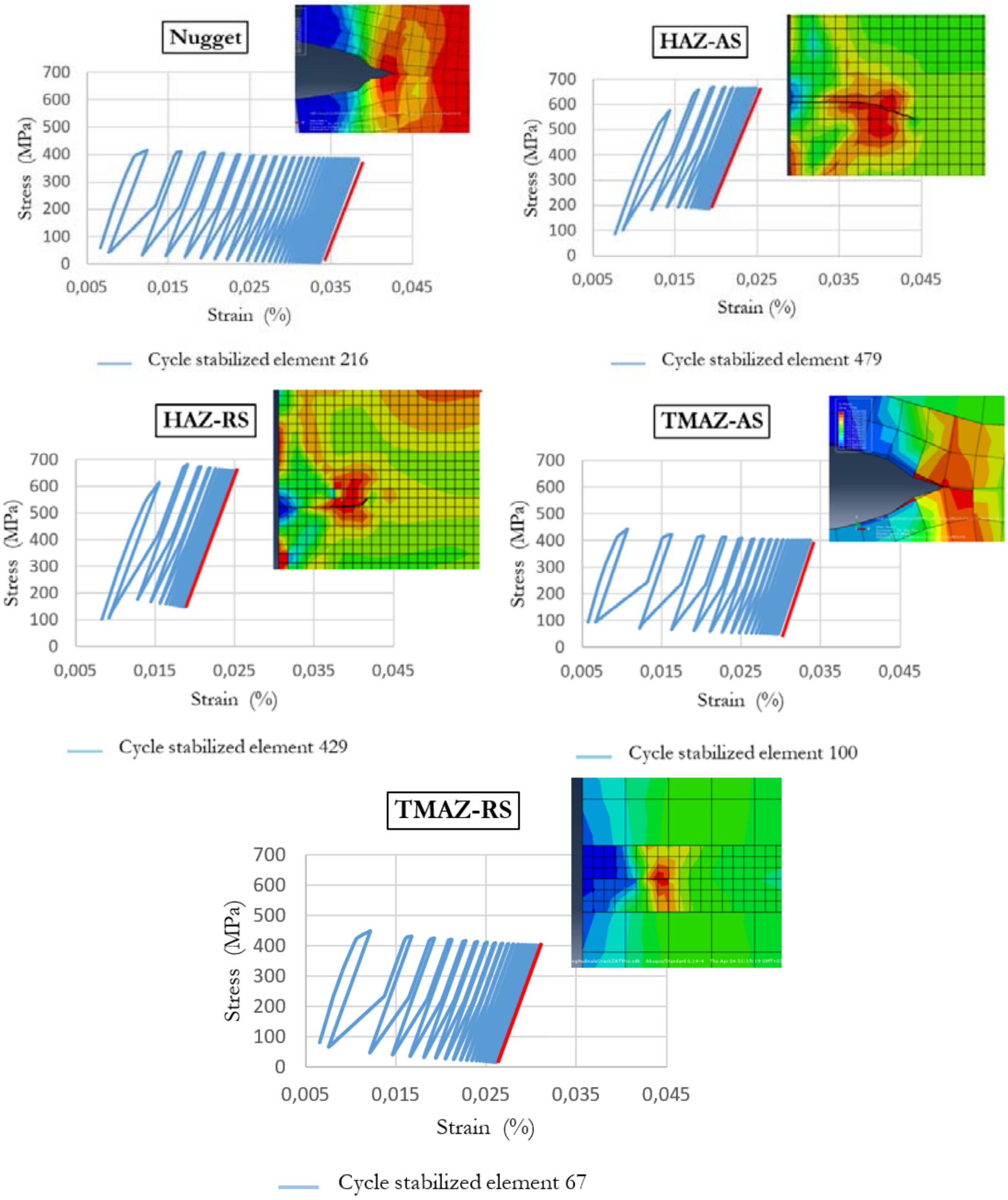

Figure 9: Stress-strain loop in each zone of the welded joint.

Fig. 8 illustrates the cyclic mechanical behaviour in each of the zones constituting the welded joint in alloy 2024-T351: ZAT (AS-RS), nugget, ZATM (AS-RS). These hysteresis loops recorded at 10^6 cycles; the solution no longer evolves. Convergence is reached and the solution is stable. The points chosen are located after the crack front, the different areas show a ratchet at the start of the test before elastic adaptation. The buckles remain a little closed throughout the test. This is the elastic adaptation phenomenon observed for each zone of the joint. Finally, the difference observed between the asymptotic behaviours of each of the zones is presented in the levels of plastic deformation which appears during the test.
It is noted that the maximum strain is well established in the nugget followed by the ZATM (AS, RS) then those are the ZAT (AS and RS) which are the least deformed.
This last phase represents the place of damage due to the levels of very important deformations. The elastic adaptation is recorded until the end of the test.
Thus, we note that the shape of the cycles is different in each finite element chosen in the structure, but we finally obtain the same adaptation response recorded at the end of the cycle.
By this analysis, we notice that the less deformed zones stabilize more quickly compared to the other zones.
These results showed that the slowest zones to stabilize correspond to the maximum deformation.

CONCLUSION

The direct cyclic method allowed to determine the local mechanical responses of the different zones of the welded joint by the FSW process of the 2024-T351 aluminum alloy. We have shown that the zones constituting this welded joint exhibit very different behaviors the ones to the others.
The numerical tests in traction-traction (R = 0.1) allowed to highlight the heterogeneities of cyclic mechanical behavior in each of the zones constituting the joint 2024-T351 welded by FSW. The curves of local behavior (σ_{22} - ε_{22}) in each of the zones made it possible to note that the various zones constituting the joint present very heterogeneous mechanical behaviors, of 0.025% of deformation in the HAZ and up to 0.038% of total deformation in the nugget, because of the strong microstructure gradient introduced by the welding process.
For the welded joint in alloy 2024-T351, the deformation field is located in the nugget followed by the ZATM and finally the ZAT.
This study showed the interest of the XFEM method for the simulation of fatigue crack propagation without remeshing or projection of the field.
The coupling of the XFEM with the direct cyclic technique, makes it possible to perform cyclic calculations and obtain the precise response of the studied structure.

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