



Experimental and Numerical Study of Friction Welding Mixing of a Thermoplastic

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November 2, 2021

Experimental and numerical study of friction welding mixing of a thermoplastic

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Abstract

This work focuses on the experimental and numerical study of mixing friction welding, a series of different experimental tests were carried out to optimize the parameters of mixing friction welding (rotation speed, welding speed and shape of the tool). We use 3 shapes of tools (square tool with flat shoulder, conical tool with flat shoulder and conical tool with concave shoulder). In this respect, a numerical approach has been studied to know the effect of welding parameters on the weld state. This approach is based on the Eulerian-Lagrangian Coupled Method (CEL), Johnson-Cook Material Behavior Law, Coulomb Friction Law and a finite element method developed under the ABAQUS/Explicit code.

Keywords: FSW, Tool Pin Profile, polypropylene, ABAQUS/Explicit

I. Introduction

Modern thermoplastic materials are increasingly used in engineering applications due to their improved stress/weight ratio, toughness, hardening time and low thermal conductivity [1] [2]. In this respect, several techniques for assembling thermoplastics have been studied. Friction mixing welding “friction stir welding” is one of the joining techniques. FSW is a process that involves complicated reactions between mechanical and thermal phenomena. These reactions affect plastic deformation and flow, heating and cooling, and dynamic recrystallization. This process consists of turning a stepped cylindrical tool with a profile probe/spindle, then slowly plunges it into the connecting line between the two pieces end to end. The parts must be properly tightened and secured to the support rod to prevent the adjacent joint surfaces from being spread apart. It is therefore essential to better understand the mixing friction welding process, to identify the evolution of the stress as a function of the welding parameters and the shape of the tool, and to better analyze the mechanical and microstructural properties. A numerical simulation is intended for the description of the method, the law of behaviour used,

the assumptions made and the conditions at the limits imposed, as well as the analysis of the formation of defects in the friction welding process.

II. Experimental methods

1. Materials used

1.1. Base Material

The basic material is PP-H homopolymer polypropylene in the form of a 4mm thick plate whose characteristics are summarized in the following table:

Table 1: Properties of polypropylene

Properties	PPs
Density, g/cm ³	0,95
Yield stress, MPa	32
Elongation at yield, %	8
Elongation at break, %	70
Tensile modulus of elasticity, MPa	1300
Notched impact strength, kJ/m ²	6
Ball indentation hardness, MPa	70
Shore hardness (D)	72
Mean coefficient of linear thermal expansion,	1,6x10 ⁻⁴
Thermal conductivity, W/m * K	0,22
Dielectric strength, kV/mm	22
Surface resistivity, Ohm	1014
Temperature range, °C	to +100

1.2. Tool materials;

The welding tool is an essential component in this operation. In this context, the choice of the latter is very important. The tool must withstand high temperature and wear. We chose to work with stainless steels. The following table presents the properties of steel.

Table 2: Steel properties

Property	Value
ρ Density [kg.m ⁻³]	7896
ν Poisson's ratio	0,25
E Elastic Modulus [MPa]	193
T _m Melting Temperature [K]	1811
T ₀ Test Temperature [K]	300
Johnson-Cook parameters:	
A [MPa]	350
B [MPa]	275
C	0.022
N	0.36
M	1
$\dot{\epsilon}_0$ [s ⁻¹]	1

2. Geometry of parts

2.1. Geometry of Welding Parts

The welding technique was performed on two polypropylene plates 4mm thick, 100mm long and 100mm wide (Figure 1)



Figure 1: Polypropylene plates

2.2. Welding Tool Geometry

Several research activities carried out over the last few years to take advantage of the FSW weld quality, show that the welding parameters and the geometry of the tool are the most influential on the condition of the weld bead. There is a variety of forms of welding tools, after the literature has been analyzed, we have chosen to work with 3 different forms presented in the following figure:



**Figure 2: Welding tool: A: square pawn with flat shoulder, B: conical pawn with flat shoulder
C: conical pawn with concave shoulder**

3. Conduct of welding tests

Experimental conditions play an important role in analyzing and understanding the phenomenon of mixing friction welding. The machine used for the welding tests is a 3-axis CNC milling machine of type [C-tek], at the National School of Engineers of Monastir whose characteristics are:

- A range of rotation speeds up to 6000 rpm.
- A feed speed range of up to 10000 mm/min.

The clamping system (Figure 3) was used for fixing the plates, which ensures uniform clamping on the surface of the plates, the purpose of which is to eliminate vibration and movement in the mixing phase.

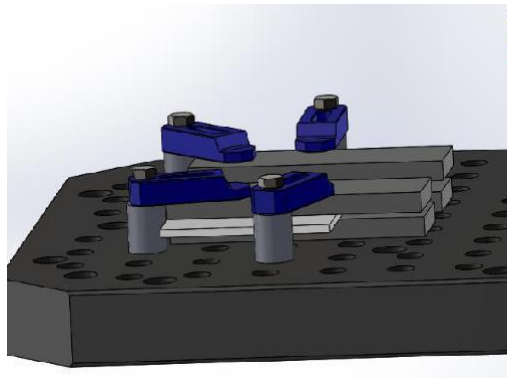


Figure 3: Polypropylene plate clamping device

The CNC machine is used to perform the welding tests. The welding operation has the same principle as the milling operation. CN Program Editor CIMCO is used (Figure 4)

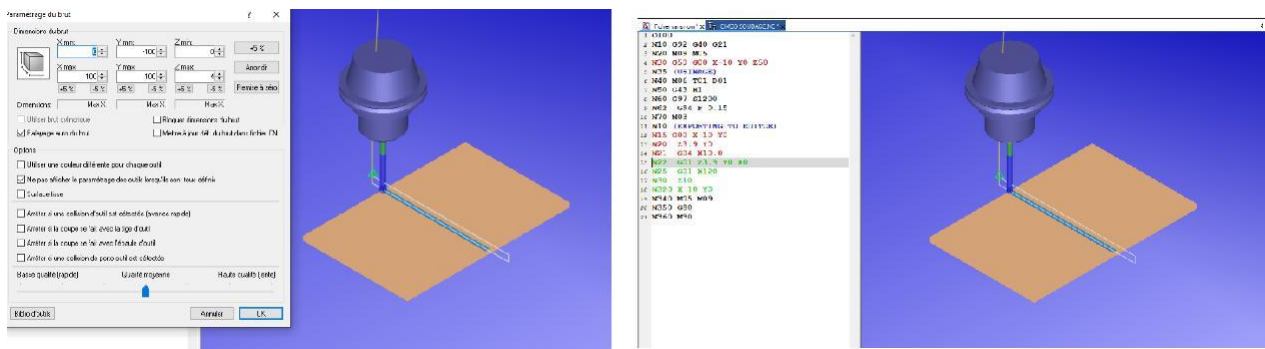


Figure 4: CIMCO programming steps

FSW parameters for polymer parts using a CNC milling machine; the spindle speed is between 500 and 2000 rpm, the feed speed is between 8 and 12 mm/min, the tilt angle is between 0 and 5° and the tool residence time is between 10s and 100s.

We set the angle of inclination to 0°, the residence time to 10s and we chose two FSW welding parameters: the feed speed (welding speed) and the rotation speed. These parameters are the most important which condition the condition of the quality of the weld joints of polypropylene. Test conditions are presented in Table 3

Table 3: Welding parameters

N number of tests	V rotation speed rpm	F feed speed mm/min
1	500	10
2	650	10
3	800	10
4	1000	10
5	500	12
6	650	12
7	800	12
8	1000	12

4: Tensile tests

For the mechanical characterization of the weld seams, the laser cutting machine in the ENIM mechanical hall was used to cut the samples in the form of tensile specimens according to ISO527. (Figure 5).

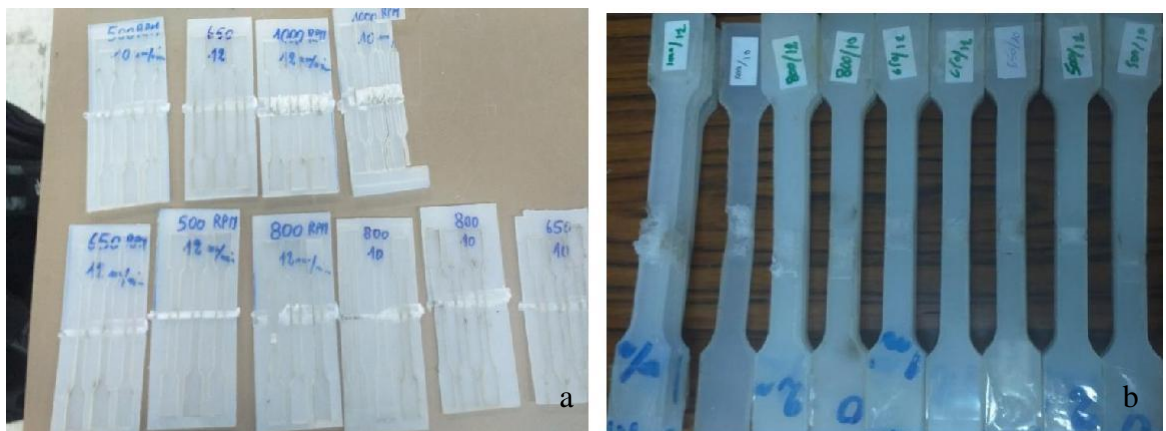
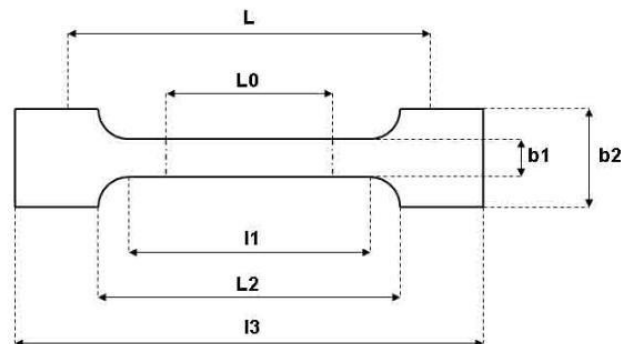


Figure 5: a: Cutting phase; b: tensile specimens

The tensile test is a useful test to identify the main mechanical characteristics of the materials, such as elastic limit, tensile strength, elongation after breaking. The tensile test sample produced is Standard ISO527-2 Type 1A and Dumbbell Form

- L0= 50 mm
- L= 115 mm
- I1= 80 mm
- I3= >150 mm
- B1= 10 mm
- B2= 20 mm
- H= 4 mm



III. Results and discussions

1. Experimental modelling

During the test, it was observed that when the rotation speed is less than 500 rpm, the heat generated is insufficient, resulting in poor welding quality. By increasing the speed of rotation to 1000 rpm/min, the material deteriorates. In addition, if the welding speed is less than 9 mm/min, high friction heat is generated, resulting in defects. In addition, when the welding speed is maintained above 12 mm / min, due to insufficient heat, a large number of voids and poor welding are caused figure 6.



Figure 6: Welding states, (a): rotation speed less than 500 rpm, (b): rotation speed more than 1000 rpm, (c):welding speed 12 mm/min

The mechanical characterization of the weld seam gave an idea of the capacity and possibility of use in industrial applications. This study is carried out through tensile tests on several states of the cord by varying the welding parameters and the shape of the tool.

Summaries the results of the tensile tests on the following histogram:

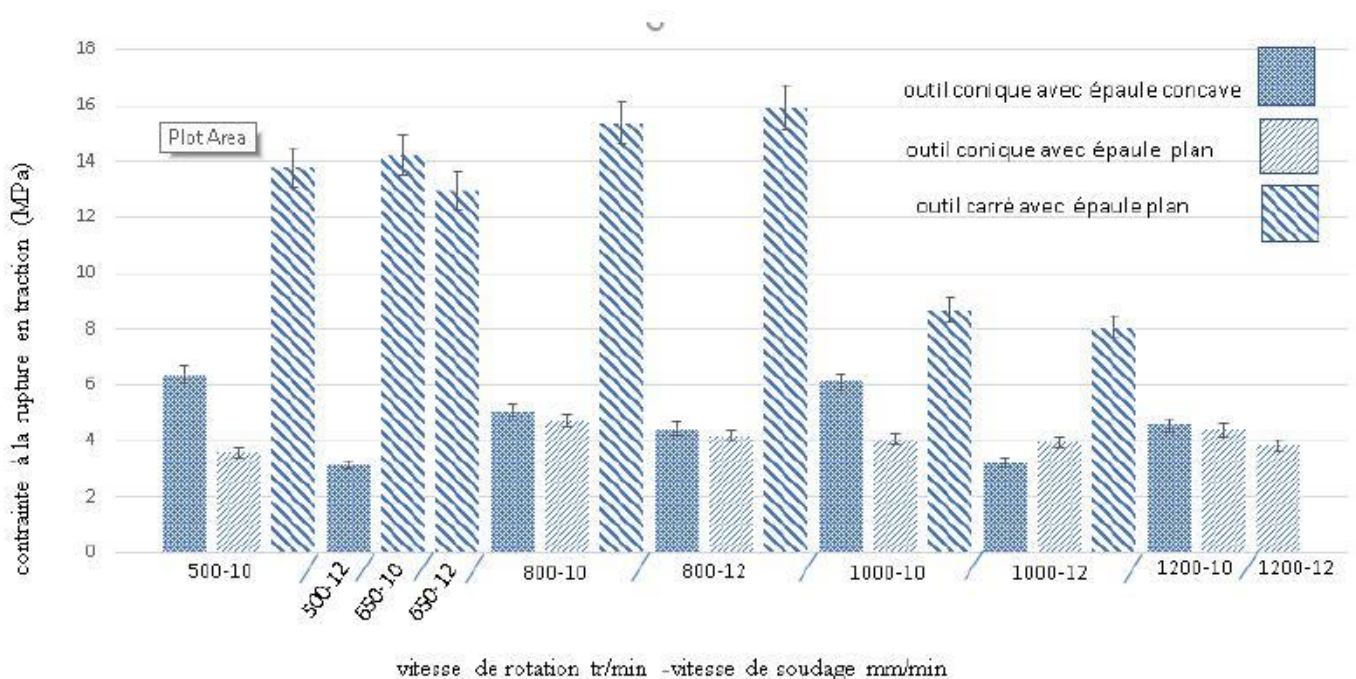


Figure 7: Effect of welding parameters on fracture stress for 3 different forms

Histogram 7 shows the effect of the speed of rotation and the speed of displacement on the tensile strength of welding, it can be deduced that the tensile strength increases to a limit speed value with the increase of the speed of rotation, then it decreases. When the tool speed is 500 rpm, the heat is insufficient, so the resistance value obtained is very low. By increasing the speed of rotation, the stirring of the spindle increases, thus the heat generated is high, which makes it possible to better mix the materials. However, as the speed of the tool is further increased to 1000 rpm, the strength of the weld decreases. The large amount of heat generated severely deforms the material. The influence of the welding speed has improved, the samples welded at 1000 rpm and 12 mm/min are better than those at 1000 rpm and 10 mm/min. Indeed, the formation of voids and the fluidity of the material is improved by increasing the welding speed.

We find that the square tool gives a good state of welding compared to the conical tool, or the value of the stress reached 15.8 MPa for the square tool. However, for the conical tool it did not exceed 6.3MPa.

2. Weld Joint Microstructure

In order to optimize the quality of the weld seams, a microstructural observation was carried out by MEB, two combinations of welding parameters were chosen for the observation: the best combination, the one that gives the best mechanical properties (Figure 8) and the second combination representing the lowest properties (Figure 7).

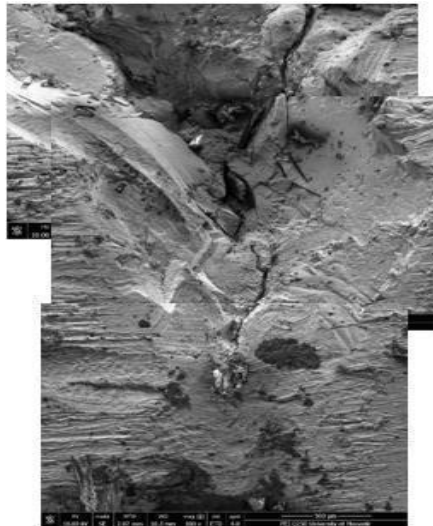


Figure 7: Weld Bead Cross-Section for 500rpm – 12mm/min (500µm Magnification)

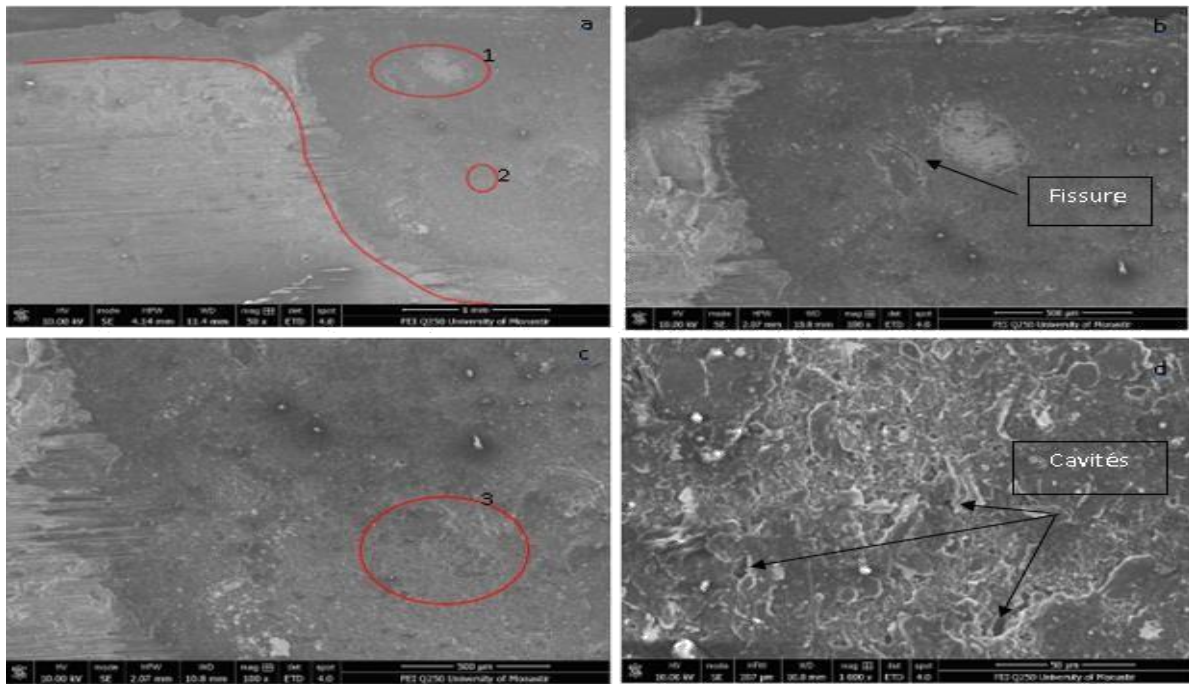


Figure 8: Weld seal defects for 800tr/min – 12mm/min observed by SEMB: (a) weld bead shape of 1mm magnification, (b) zoom “1” defect of 500 μ m magnification, (c) zoom “2” of 500 μ m magnification, (d) zoom “3” defect of 50 μ m magnification

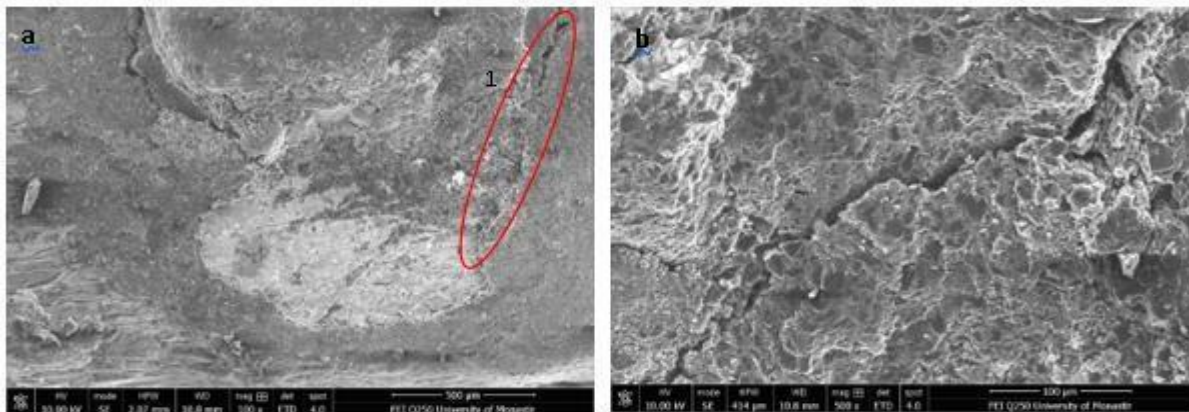


Figure 9:(a) defects located at the end of the weld bead for 800tr/mi -12mm/min of 500 μ m magnification ,(b) zoom of the 100 μ m magnification area 1

The weld seams are represented in different forms observed by SEM, at first sight (Figure 7), the SZ zone (core) is small and the existence of defects in the form of macroscopic crack, In second view (Figure 8), a well-formed kneaded weld seam, marks the presence of microscopic defects that become macroscopic at the low level of the cord (Figure 9) under the effect of the temperature gradient.

3. Numerical modeling

Numerical modelling aims to study the physical mechanisms of friction welding kneading. The majority of the models are solved by the finite element method which uses the balance equations to determine the deformation and temperature profile. For this, it is necessary to add the law of material behavior to solve mathematical formulations. We can distinguish three laws that are most used for modeling the FSW process, such as the Power Law (Norton hoff) the Sellars-Teggart Law (ST) and the Johnson-Cook Law.

Our model is viscoplastic in this case the Johnson-Cook behavior model is the most adaptable. This model has an unrealistic dependence on the rate of deformation of high temperatures.

It is known that rotation speed and feed speed are the most influential parameters on weld quality and defect formation during the mixing friction welding process. We vary each time one of the parameters of the welding, We obtain the following results

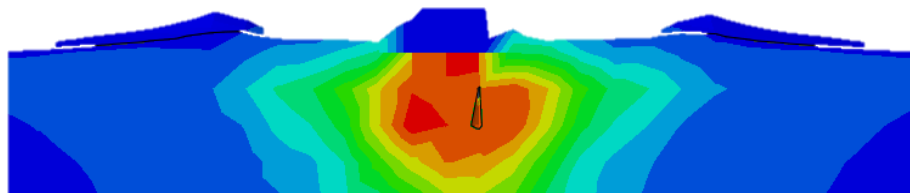
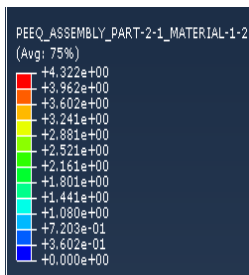


Figure 10: Equivalent plastic deformation and vacuum formed at 500 rpm

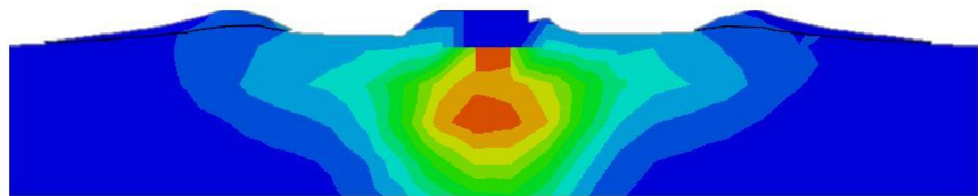
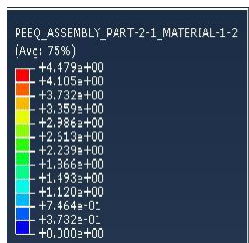


Figure 11: Equivalent plastic deformation and vacuum formed at 800 rpm

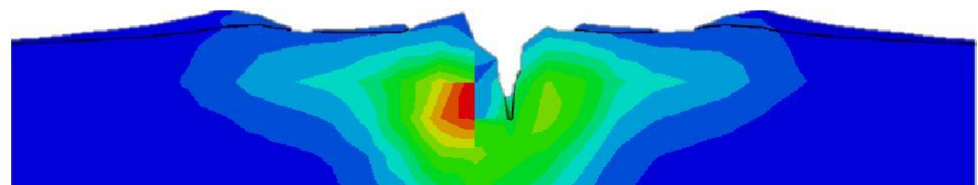
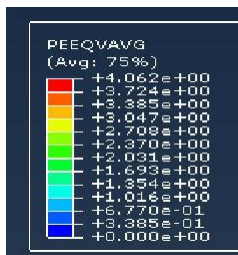


Figure 12: Equivalent plastic deformation and vacuum formed for 12 mm/min

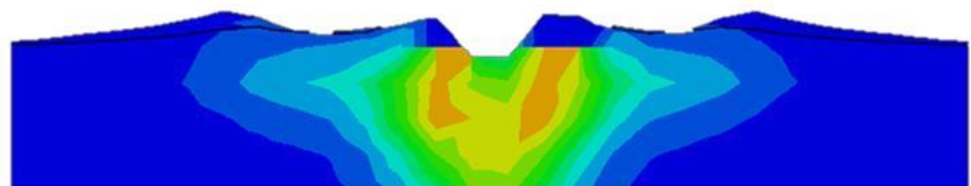
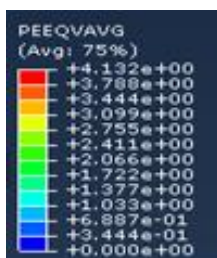


Figure 13: Equivalent plastic deformation and vacuum formed for 10 mm/min

It is observed that the model can discover quite precisely the shape of the plasticized area and the presence of voids in the weld. The presence of the vacuum is directly affected by the welding parameters, low advance welding and high rotation speed ensures a smaller vacuum.

IV. Conclusion

This work focuses on the experimental and numerical study of mixing friction welding, an experimental study is conducted on polypropylene (PP). The welding tools used are: A conical tool with flat shoulder, a conical tool with concave shoulder and a square tool with flat stainless steel shoulder and a numerical study is developed using the calculation code Abaqus, the objective of this study is the analysis of the equivalent deformation for a square tool under the effect of the welding parameters.

This experimental and numerical study allowed us to conclude that:

- The tensile fracture stress is mainly affected by the advance, the rotation of the tool and second by the shape of the tool.
- As the temperature gradient between the top and bottom of the weld is different, the crack size is also different, the cracks are small (microscopic) up and down.
- The equivalent deformation is sensitive to the variation of these parameters.

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