Development and modeling of hot tearing test in TIG welding of aluminum alloy 6056

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Development and modeling of hot tearing test in TIG welding of aluminum alloy 6056

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Abstract

TIG welding process is widely used in the aeronautic industry. However, the increase of productivity which generally require an increase of welding speed is limited by the appearance of defects, such as hot tearing. This study focuses on the analysis of hot tearing in TIG welding on a 6056 aluminum alloy, used in aircraft manufacturing. Thanks to the developpement of an original hot tearing test and to numerical simulation of welding process, the influence of various process parameters on the occurrence of hot cracking has been investigated.

1 Introduction

Welding processes are extensively used to assembly components in many manufacturing industries, such as aeronautic, construction, energy and automotive. To increase their productivity, constructors try to reduce manufacturing time. This involves for welding operations an increase of welding speed. However, various defects such as hot tearing then appear. These defects strongly affect the weld quality and then mechanical strength of welded components. In figure 1 , a crack created during arc welding on a 6056 aluminum alloy is clearly visible. The purpose of this research is to explore ways for optimizing the welding parameters with respect to hot tearing.

Figure 1: Hot tearing in TIG welding

This paper first presents the TIG welding process and hot tearing phenomenon [1]. Then an original test developed for hot tearing characterization in welding is presented. Next, experimental results achieved in TIG welding on aluminum alloy 6056 are analyzed. In parallel to this experimental investigation, a thermomechanical modelling of the welding operation will be developed [2].

2 Hot tearing phenomenon in welding

2.1 TIG arc welding process

The 'Tungsten Inert Gas' process (TIG), also called Gas Tungsten Arc Welding (GTAW) is a welding process using a tungsten refractory electrode to create an electric arc, and an inert gas, generally argon, to protect metal against oxidation. The arc created between the end of the electrode ant the components to be welded causes a local melting of the metal. Defects in welding are numerous. They may be related to metallurgical factors, to welding parameters, or to environmental conditions. Among the main welding defects, hot and cold tearing, porosity, corrosion or sticking can be quoted. In this work, we focus on hot tearing. This defect appears during welding, at the end of solidification and strongly affects the mechanical strength of assembled parts.

2.2 Hot tearing

Hot tearing phenomenon appears during solidification of an alloy, so it can observed during welding, but also during casting or other processes involving solidification. This section describes the mechanisms of crack initiation and the main factors responsible of this phenomenon.

During welding, components are subjected to high thermal gradients around the melting zone due to localized heat input. The solidification area is located at the rear of the melting zone. In alloy, liquid / solid change begins at the liquidus temperature and end at the solidus temperature. Mushy zone corresponds to the coexistence of liquid and solid phases. Hot tearing phenomenon is correlated to the microstructure evolution in this mushy zone.

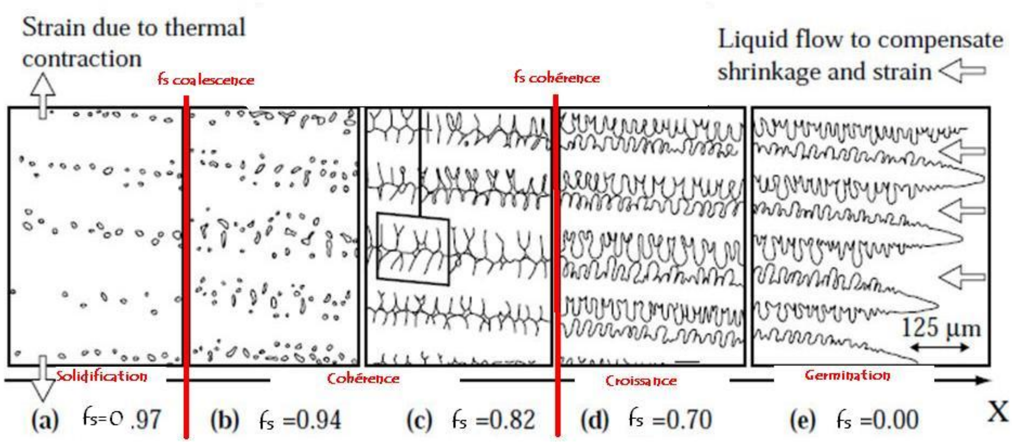

Figure 2: Evolution of the microsturcture of the mushy zone as a function of temperature

During solidification of alloy, the microtructure changes in 4 stages to achieve the solid state.

- germination: it is the first stage of solidification. Solid particles then germinate in a large quantity of liquid. The material behavior is similar to a viscous fluid.
- growth: the solid fraction increases gradually and the temperature approaches the solidus. In welding, the temperature gradient is very important, so the solidification front (solid liquid interface) is dendritic.
- cohesion: solid fraction begins to be high. The dendrites are in contact with each other and form a coherent solid skeleton. The fall of the permeability is then observed due to the formation of a

continuous solid network. Thin liquid films between the solid grains remain and are subjected to high strain, mainly due to solidification shrinkage and thermal contraction of the solid. During this stage, the strain to fracture of the alloy is very weak, because the liquid can no longer flow to accommodate deformation and solid network is not enough resistant to avoid cracking.

- solidification: the solid fraction tends to 1 and the last pockets of liquid solidifies. A strong solid network can then resist to strain. The stress and strain to fracture is rising rapidly.

Brittle Temperature Range (BTR) corresponds to the solid fractions where the microstructure is in critical configuration. Hot tearing risk is maximum in this temperature range. Figure 2 shows dendritic grain growth during solidification as a function of solid fraction. The BTR corresponds to the interval between the coherency solid fraction, where the liquid does not easly circulate because of the low permeability, and the solid fraction of coalescence, where the solid opposes mechanical resistance.

During welding, the mushy zone undergoes during solidification, mechanical stresses due to thermal and mechanical loading. Indeed, high speed cooling after welding implies a solidification shrinkage (due to phase change) and the thermal contraction of the solid skeleton (which depends on the expansion coefficient of the solid already formed). Added to these thermal strains, external constraints clamping prevents the natural distortion. All these stresses can cause the decohesion of liquid films creating the cracks.

Hot tearing occurence is related to process parameters, such as welding power and welding speed but also to the material used. The chemical composition of material and its solidification mode modifie the quantity of residual elements with low melting point favoring the residual liquid films decohesion. Moreover, thermal expansion of the alloy and the size and shape of grains play on the material sensitivity to cracks.

3 The experimental system

Initiation of crack is controlled by metallurgical factors, such as solidification range, grain size and shape, mushy zone permeability and to mechanical factors, such as stresses, strains and strain rates acting over the mushy zone. The purpose of this work is to study the interaction between mechanical and metallurgical factors in order to better identify the parameters influencing the hot tearing phenomenon in welding. Originality of this study is to try distinguishing the structural effects on a global scale in the face of the microstructural effects on a local scale.

3.1 Hot tearing test

Several tests have been previously developed in order to characterize material ability to hot tearing [1]. These tests allow to classify the alloys according to their sensitivity but does not develop quantitative criteria for each material.

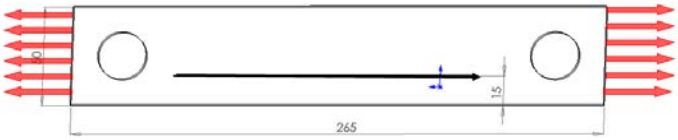

Figure 3: Specimen longitudinal tensile with fusion line TIG

A simple original hot tearing test for thin plates has been developped in this study. The originality of this test is to apply a controlled tensile pre-stress in welding direction on a rectangular sample cut on thin 6056 aluminuim plates of 0.8 to 3 mm thicknesses (figure 3).

During welding, the specimen is clamped on both sides between two jaws. A fusion line is made with TIG arc welding process on the center of the thin aluminum plates. The advantage of this test, compared to other hot tearing tests such as Varestraint test [3], is its simplicity which is interesting for an industrial use. In addition, the simple sample geometry and boundary conditions make easy the 2D numerical simulation of the test.

In this test, the of microstructure is possible by adjusting thermal cycle, depending on welding power and speed and samples size especially. Microstructural characteristics are observed using high speed camera recording and post mortem analysis. Mechanical factors are controled by welding parameters adjustments and control by the pre-stress applied thanks to the clamping system.

Hot tearing test is placed on a mobile two axes (X, Y) table, figure 4. In that way, the high speed camera is static to observe the rear of the weld pool.

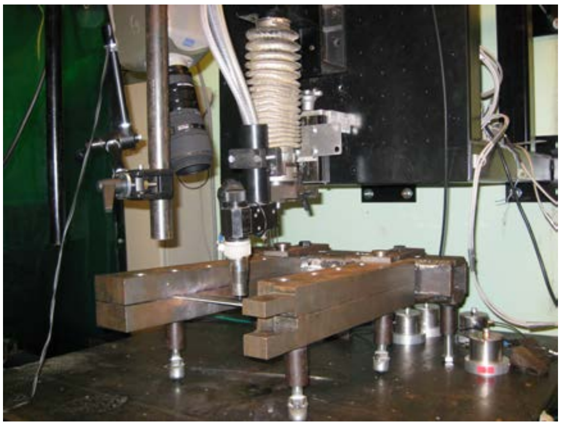

Figure 4: Two axes table with hot tearing test

The first test campaign was achieved to validate experimental device. The 6056 alloy specimens, of dimensions 265 * 50 mm were water jet machined from 2.3 mm thick plates. During all these tests, a 200 MPa preload is applied, the welding parameters (speed and intensity) are changed.

3.2 Experimental results

The results of this first test campaign allow to classify welding parameters as cracking or not cracking conditions. High welding speeds in the range 5 mm/s - 20 mm/s and 130 A - 260 A range welding current were chosen. A 3 mm arc length is imposed for all the welding tests, which correspond to a welding tension of about 10 V. Crack initiation occured once steady state thermal conditions are reached. Figure 6 shows the crack sensibility evolution of 6056 alloy as a fonction of welding parameters.

Figure 5: Penetrant testing in cracking specimen

This curve coupled with penetrant testing results, figure 5 , highlight several failure modes, depending on process parameters. For high welding speed, some small transverse cracks are observed on the edges of the weld, that deviate rapidly to propagate in a large longitudinal crack (Figure 5). At the opposite, for low welding speed, the transverse cracks observed are more numerous, and does not

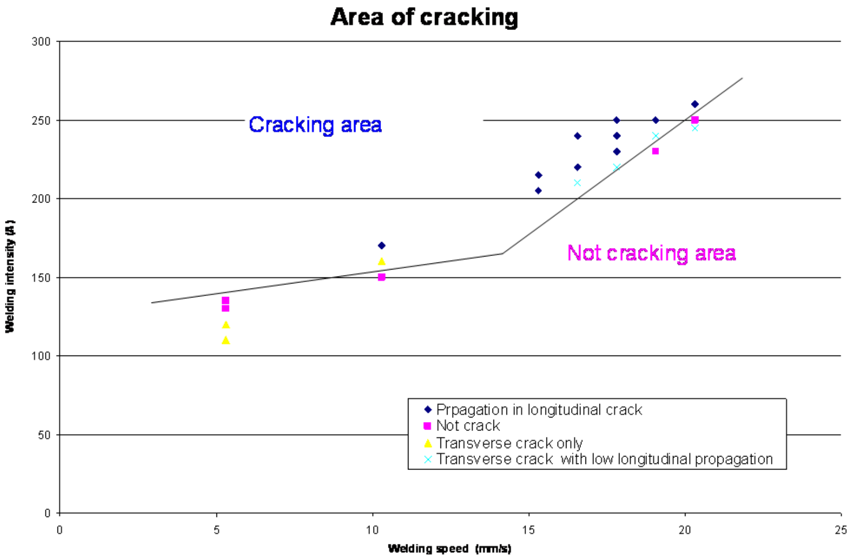

Figure 6: Hot cracking area

deviate in a longitudinal direction. It is well known in literature, dendritic columnar grains are more sensitive to hot tearing than equiaxe grains [4].

Microscopy analysis shows melting zone is always divided into a columnar dendrite zone on the edges and a equiaxe dendrite zone in the center, which the size of each zone depends on the welding parameters. Observations of cracks at a higher magnification indicates a interdentritic fracture, typical of the hot tearing phenomenon figure 7. The grain morphology formed in the center part of the weld is then favorable to prevent hot tearing. This is why the cracks always initiate in the columnar zone of the weld, in a transverse direction. For the lower welding speeds, the cracks are stopped by equiaxe grains, then cracks remain short. At the opposite, for high welding speed, cracks initiated in the columnar zone propagate in the equiaxe zone, to form a large and very critical longitudinal crack.

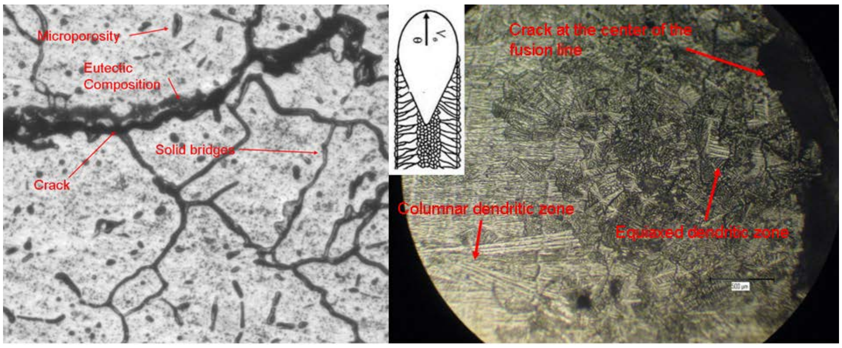

Figure 7: Hot crack micrograph formed during welding of 6056 alloy (x 100) / columnar and equiaxe zone formed during welding of 6056 alloy

In addition to the post mortem analyses high speed camera recording of the mushy zone were made, in order to try to observe crack initiation. Mushy zone observation is complicated by the oxide formed at the weld pool. With an improved gas protection, the weld pool liquidus boundary appears (figure 8), and observation of the mushy zone is possible. We expect of these in-situ observations a better understanding of the hot tearing initiation concerning the solid fraction and dendrite morphology.

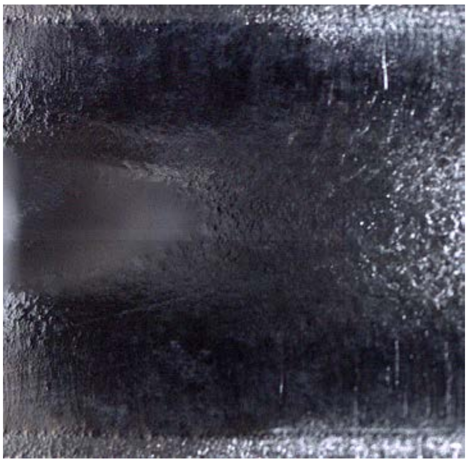

Figure 8: Image from the video recording during welding

4 The numerical simulation of welding

4.1 Welding process modelling

Modeling thermomechanical processes is of great interest to researchers. Leblond et al. have proposed comprehensive models to take into account all the phenomena involved during welding or heat treatment of metals [2].

During a welding operation, the physical phenomena can be listed in three categories:

- thermal : heat source,latent heat, conduction and convection;
- metallurgical : phase expansions, microstructural changes;
- mechanical : deformations and residual stresses induced during welding.

Numerical simulations were performed using the finite element commercial code Sysweld. The calculations were conducted in a 2D configuration on the surface of the plate, considering a plane stress state.

The mesh are coarse around the fusion line and is refined in the molten zone. The heat source is modeled by a surface Gaussian distribution. This source is moving at a 15 mm/s speed. Convection and radiation thermal exchanges are taken into account. All thermal and mechanical properties, except Poisson's ratio, are considered to be temperature dependent. The mechanical properties of the material are modeled using an elasto-viscoplastic model with an isotropic strain hardening.

4.2 Simulation Results

Simulation is used to show influence of tensile pre-stress on mushy zone. Two cases are studied here : a specimen subjected to longitudinal tensile stress and a second not clamped. Plastic strain evolution, in figure 9, changes according to temperature. The mechanical history of two nodes on the melting zone are studied. Node 8153 is located in the central axis of the weld and node 6343 is located in the edge of melting zone. We will focus on plastic strain evolution during cooling and mainly at solidification end, which is critical range for hot tearing. Previous experimental results have shown that crack initiation appears at the edge of the melting zone in a transverse direction. So we first observed longitudinal strain at node 6343 (edge of the weld pool). In figure 9, it can be observed longitudinal plastic strains with tensile stress at the solidification range are larger than test without tensile pre stress. Mushy zone with this develloped test is subjected to positive deformation. Longitudinal pre stress promotes transversal crack initiation. For the transversale strain in the center node, there is a positive deformation at solidification beginning, slightly higher in cases with tensile pre stress. Crack propagation is facilitated by longitudinal pre stress.

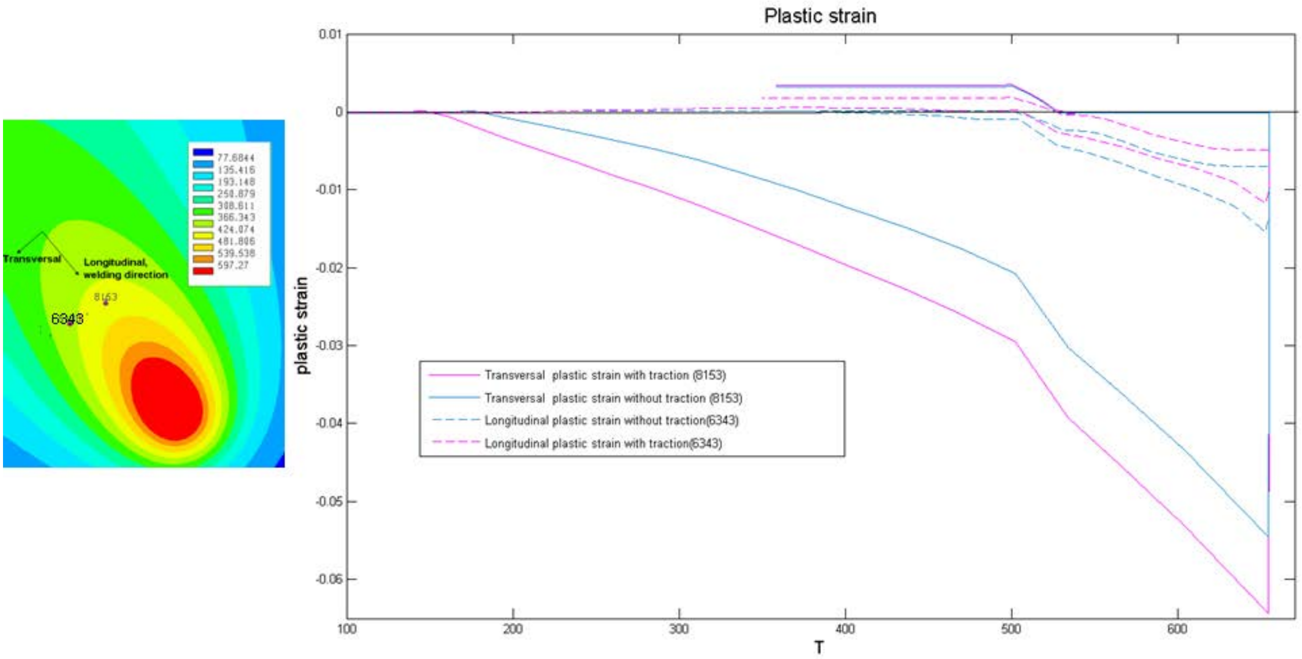

Figure 9: Strain evolution during welding

5 Conclusion and prospects

It has been demonstrated that solidification cracking is a many faceted problem, with many influencing parameters. A lot of study examines hot cracking but few studied relationship between mechanical aspect induced by process and microstructure. The developed test in this study is a simple test and used by industry. It allows the initiation of the crack du to welding parameters, material and pre-stress applied. Tensile effect on the mushy zone is highlighted by numerical simulation. Observation using hight speed camera will better understand the mechanisms of crack initiation and also a bifurcation at the grain scale.

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