Hot tearing test for TIG welding of aluminium alloys: application of a tensile load parallel to the fusion line

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Abstract

Defects control such as hot cracking in aluminum alloys welding is an important industrial issue. Understanding of hot cracking phenomenon is a complex problem involving process, material and mechanical loading due to clamping. Several tests have been previously developed in order to characterize the material propensity to hot cracking. The purpose of the present work is to study, using a new hot cracking test and numerical simulation, the relationship between mechanical and metallurgical factors in order to better identify the parameters leading to hot tearing during welding.

The originality of the test presented here is that an external stress is applied on the test specimen parallel to the welding direction. The advantage of this test, compared to others like Varestraint test, is its simplicity which is interesting for an industrial use. A fusion line is made with a Tungsten Inert Gas (TIG) arc welding process on a thin sheet of aluminum alloy (6061). The crack initiation occurs once steady state thermal conditions are reached. The present test enables to distinguish between the structural effects on a global scale and the microstructural effects on a local scale. Microstructure control is made possible by adjusting welding power, welding speed and sample geometries. The grain morphology plays a crucial role in the crack initiation. It depends on the intensity and the welding speed and the specimen geometry. It is characterized by the shape, size but also the direction of grain growth that influence the cracks initiation. Microstructural features are observed using high speed camera recording and post mortem micrographs. Mechanical factors are varied by adjusting the welding parameters and the applied pre-stress. The relationship between welding parameters, morphology of the

generated grain structure, and sensitivity to hot cracking were discussed. Experimental measurements and numerical results will help to better determine global and local conditions at the onset of hot tearing and to compare those conditions using existing hot tearing criteria.

Introduction

Welding processes are extensively used to assemble components in many manufacturing industries, such as aeronautics, 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. In figure 1, a crack created during arc welding on a 6061 aluminum alloy is clearly visible. The purpose of this research is to explore ways for optimizing the welding parameters with respect to hot tearing. These defects strongly affect the weld quality and then mechanical strength of welded components.

Welding process promotes hot cracking phenomenon due to the liquid / solid phase change. Many aspects must be taken into account to reduce the cracking risk. This complex phenomenon, involving metallurgical and mechanical factors, is studied using a new test. Metallurgical factors involved include especially the solidification range, grain size and shape, which alter the permeability of the mushy zone. This work proposes to study the interaction between the process, the material and the mechanical loading in order to reduce hot cracking sensitivity.

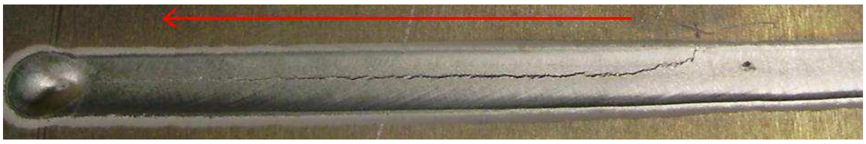

Fig. 1. Hot tearing in TIG welding.

This paper first presents the hot cracking phenomenon. Then an original test developed for hot tearing characterization in welding is presented. Next, experimental results achieved in TIG welding on aluminum alloy 6061 are analyzed. In parallel to this experimental investigation, a thermo-mechanical modeling of the welding operation is developed. Finally, the analysis of the microstructure influence on susceptibility to hot cracking is discussed in order to propose improvements to the welding process.

Hot cracking phenomenon in welding

Defects caused by welding operation are numerous and can be related to metallurgical factors, welding parameters or external conditions. Among the main welding defects, hot and cold tearing, porosity, corrosion or sticking can be quoted. Hot tearing phenomenon appears at the solidification end of an alloy, and is commonly observed in welding. This section describes the mechanisms of hot crack initiation and the main factors responsible for 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. During slow cooling, this zone is bordered by two isothermal surfaces corresponding to liquidus and solidus temperatures. The mushy zone corresponds to the coexistence of liquid and solid phases. Hot tearing phenomenon is correlated to the microstructure evolution in this mushy zone at the rear of the melting zone.

The solidification is divided into four stages (figure 2) [14]. Germination is the first step, solid particles germinate in a large quantity of liquid. The material behaves like a viscous fluid with a very low tensile strength. Then, the grains grow. The solid fraction increases gradually and the temperature approaches the solidus. During welding, the solidification rate is high, and the solidification front (solid-liquid interface) is dendritic type. The cohesion solid fraction is then achieved. The dendritic grains are in contact with each other and form a coherent solid skeleton. A sharp drop in permeability is then observed, due to the compact network formation. Thin liquid films between the solid grains remain and are subjected to high strains, 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 resistant enough to avoid cracking. Finally, the last stage corresponds to solidification of the last liquid pockets, where the solid fraction tends toward one. The solid network can then resist to strain. The stress and strain to tensile failure is rising rapidly.

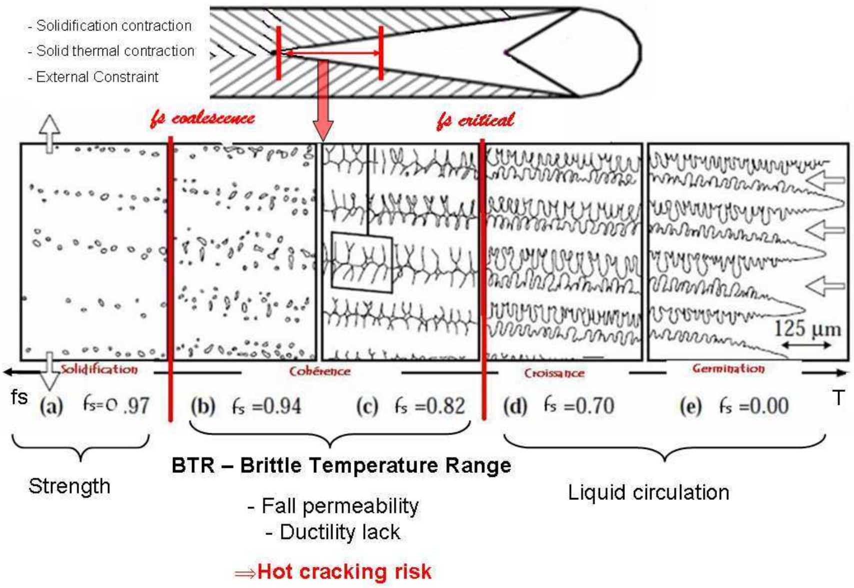

Fig. 2. Microstructure evolution in the mushy zone.

Brittle Temperature Range (BTR) is defined as the temperature interval corresponding to the solid fractions where the microstructure is in critical configuration. Hot tearing risk is maximal 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 easily circulate because of the low permeability, and the coalescence solid fraction, where the solid opposes mechanical resistance due to rise of the number of solid bridges formed.

In welding, the mushy zone undergoes thermal and mechanical stresses during solidification. Resulting stress and strain fields are very complex to predict due to two main factors. The first one is the result of differential shrinkage imposed by high temperature gradients. The second one is a consequence of the mechanical properties thermal dependence on different phases. Several parameters related to the material through its solidification path and its alloying elements, to the characteristics of the thermal loading, to the microstructure and mechanical clamping should be taken into account to analyze stress and strain evolutions [2]. All these stresses can cause liquid films to debond and/or solid bridges to break causing crack initiation.

Hot tearing occurrence is then related to process parameters, such as welding current and welding speed, but also to the composition of the material used. The solidification conditions play an important role in susceptibility to hot cracking. The chemical composition of material and its solidification mode modify the quantity of residual elements with low melting point favoring the residual liquid films decohesion. The aluminum alloy used in this study, the 6061, is very sensitive to hot cracking due to its wide solidification range. This alloy has structural hardening, so its high temperature behavior is complex.

Thermal contraction is the main factor of mechanical loading in the mushy zone. The thermal gradient, imposed by process, affects solidification microstructure and heat distribution in the sheet, which change mechanical loading. From a mechanical point of view, the welding process leads to a non uniform distribution of temperature, combined with thermal stresses and localized plastic deformation. The stress fields and strain distribution strongly influences the BTR loading. The non-uniformity of thermal loading and the nonlinearity of the mechanical behavior of the material, however, make complex phenomenon understandable.

The experimental system

It has been seen in the previous section that crack initiation is controlled by metallurgical factors, such as solidification range, grain size and shape, mushy zone permeability, and by mechanical factors, such as stresses, strains and strain rates acting on 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. The originality of this study is to try to distinguish the process influence on hot cracking by experimental and numerical results.

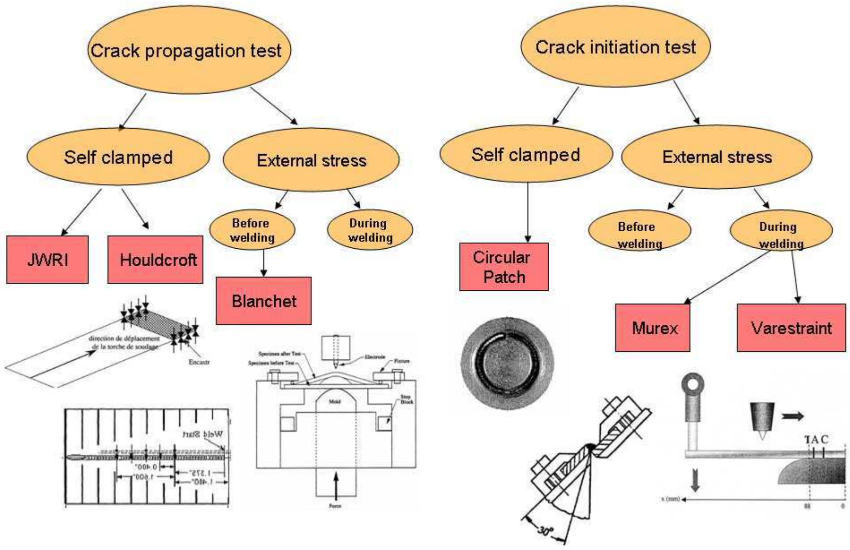

Fig. 3. Cracking test: state of art.

To assess hot cracking sensitivity of an alloy, various tests have been developed [3]. In figure 3, the existing tests have been classified into two categories: crack initiation tests (Varestraint test type) and propagation tests (JWRI test type). The mechanical stress applied can be external to the specimen or produced by self clamping. These tests are generally difficult to interpret and implement in an industrial setting. Moreover, it is difficult to distinguish the sample geometry effects and the process effects, because cracks are the result of complex interactions between these factors. A new hot tearing test has been developed to better understand the process parameters influence on the sensitivity to crack initiation.

A simple original hot tearing test for thin sheets has been developed in this study. The aim is to impose an external and controlled mechanical loading promoting cracking, to study the process and material influence on hot cracking susceptibility. This test should help to initiate the phenomenon under controlled experimental conditions. Indeed, controlled mechanical loading is defined as a constant in hot tearing analysis.

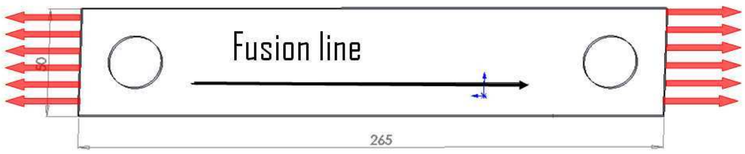

Fig. 4. Longitudinal tensile specimen with TIG fusion line.

The test originality is to promote crack initiation through a single solicitation. It involves applying a controlled tensile preload in the welding direction, before making a fusion line without filler metal (figure 4). During welding, the specimen is clamped on both sides between two jaws. The process used is the Tungsten Inert Gas process (TIG), also called Gas Tungsten Arc Welding (GTAW), a welding process using a tungsten refractory electrode to create an electric arc, and an inert gas, generally argon, to protect metal against oxidation. A fusion line is made on a parallelepiped sample in the longitudinal direction. Hot tearing test is placed on a mobile two axes (X, Y) table, figure 5. During a welding test, welding arc is in a fixed position, and sample is translated in the longitudinal direction at constant speed. The used sheets are thin (<3mm) and samples, cut with a water jet machine, have a 265x50mm² size. Displacement of the fusion line from the sample symmetry axis to one sample side (figure 4), or change of tensile pre-stress value, allow to investigate structural effects on hot tearing.

The test advantage, compared to other hot tearing tests such as Varestraint test, is its simplicity which is interesting for an industrial use. In addition, the simple sample geometry and boundary conditions make the 2D numerical simulation of the test easy. In this test, control 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. The high speed camera is in static position to observe the weld pool rear. Mechanical loading is controlled by welding parameters adjustments and by the pre-stress applied thanks to the clamping system.

Six welding speeds, between 5 mm/s and 20 mm/s, were studied. Four tests were conducted for each speed by varying the welding current in the range [130A, 260A]. The alternative current in TIG welding is necessary on aluminum. At each cycle, there is a polarity reversal that breaks the alumina layer formed on the surface. The ratio welding current / welding speed is set to have full penetration. A 3 mm arc length is imposed for all the welding tests, which corresponds to a welding tension of about 10 V. In total, 24 samples have been studied with varying welding parameters and a fixed pre- stress of 200 MPa (0,8 mm initial displacement imposed at the sample end). Note that the welding speed range is rather high for TIG welding process.

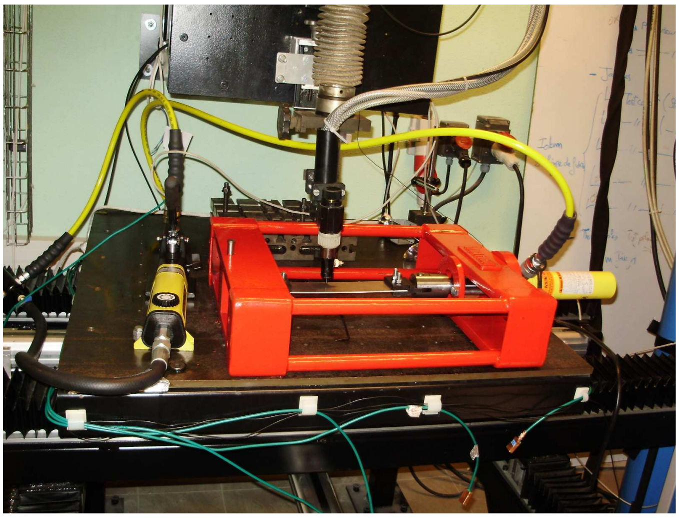

Fig. 5. Two axes table with hot tearing test.

These tests allow the cracks initiation in quasi-stationary state, in the mushy zone where complex solidification mechanisms are observed. Crack initiates, for all conditions tested, transversely to the welding direction and then propagates along the center line (figure 1). This simple test has been developed to identify the external clamping effect and the process influence on crack initiation. The factors most frequently cited as affecting hot cracking are the welding process parameters, mainly the welding speed and welding current, the material composition and the mechanical stress. Cracks are thus connected to the material, through the nature, size, morphologies, grain orientation and the stress generated by welding cycle and clamping. The focus is specifically made on the preload influence on hot cracking during solidification.

The study of complex coupling between process, material and mechanical loading requires an experimental investigation but also a numerical analysis for hot cracking study. Indeed, it is necessary to have information on the strain and stress field around the welding pool during cycle to better understand cracking mechanism.

Numerical validation of test

Chihoski [4] was the first to study stress distribution due to a very localized heat input on thin sheets of aluminum alloy. The non-uniformity of thermal loading and the mechanical behavior nonlinearity of the material make complex phenomenon understandable. The stress distribution complexity during welding requires the finite element modeling support.

A modeling approach to hot cracking in welding involves taking into account the thermal and mechanical problems to evaluate the strain and stress distributions during welding but also the thermal- metallurgical problem by assessing microstructural parameters. A simulation (with Sysweld finite element software) of a fusion line in TIG process is made on a thin sheet of aluminum alloy, hence the choice of 2D modeling. A displacement producing a stress equivalent to the material yield stress (about 200MPa) is applied as boundary condition to the sample before welding, as shown in the previous section. The tensile preload and the welding direction are along y axis (figure 6). The heat source model is Gaussian type and welding speed is 15 mm/s. The geometrical modeling of metal sheet is made with a fine mesh in the welded region. The purpose of this section is to understand the preload influence on stress and strain field in the mushy zone.

Stresses and strains are generated by structural mechanisms corresponding to external loading, thermal loading induced by the process and heterogeneity of the mechanical behavior in different areas due to thermal gradient. The thermal dependence of Young's modulus, thermal expansion coefficient and yield strength is taken into account. The weld pool shape and size are directly related to the thermal loading. The weld pool geometry has a strong influence on the stress and strain distribution. An elongated bath representative of our experimental results is simulated by adjusting the heat source parameters. This relatively simple model was applied to the test geometry to study the preload influence on the susceptibility to hot cracking. Then, this model will be used to propose optimization ways of welding process in order to limit the crack initiation.

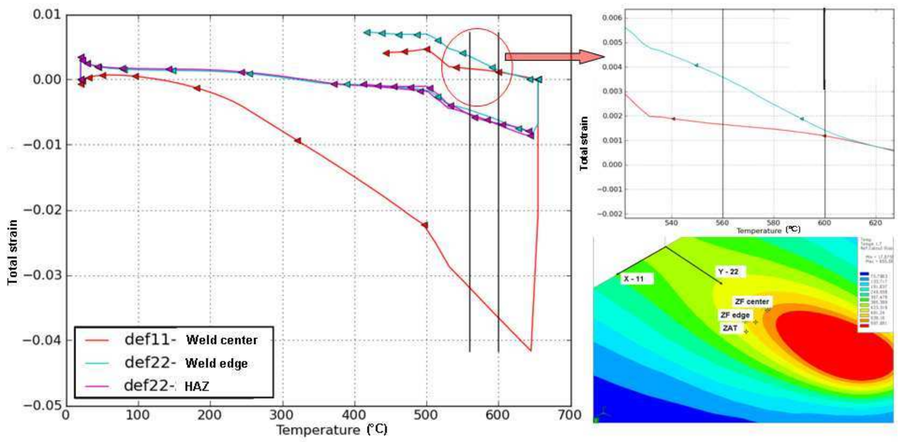

Fig.6. Strains evolution for developed test.

Figure 6 shows the strain evolution during thermal loading in three points of the weld pool: one point in the weld center, one in the mushy zone at the weld edge and the last in the heat-affected zone. The normal strain (ε11), transverse to the weld, is shown in the weld center. For two other points, we have chosen to represent the longitudinal strain (ε22). These points and strain direction were chosen in agreement with cracks location and orientation experimentally observed. In critical range, represented by two vertical black lines in figure 6, the strain evolution promotes hot cracking in the weld. Indeed, the weld edge is subject to positive strain, mainly due to the shrinkage, thus facilitating cracks initiation. Moreover, results in figure 6 show a positive longitudinal strain rate at the solidification end, most important for point located at the weld edge, in the mushy zone.

For the transversal strain in the weld center, there is a positive strain at solidification end which facilitates crack propagation. The total strain at the point located at the weld center (transverse tensile) is twice lower than on the weld edge in the mushy zone (longitudinal tensile) in the BTR which is in accordance with experimental observations, cracks always initiating transversely, in the weld edge. The liquation risk is limited, the point situated in heat affected zone presenting a negative strain.

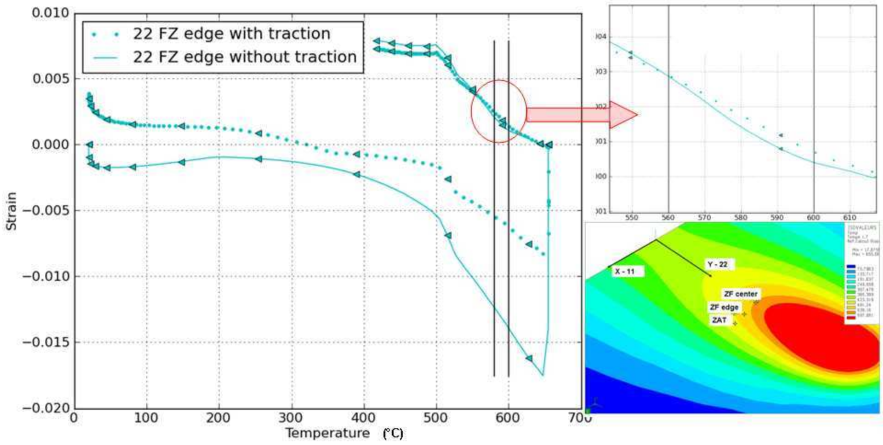

Fig.7. Strains comparison.

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. Total strain evolution, in figure 7, changes according to temperature and only the longitudinal strain evolution of point situated at the weld edge is studied. In the BTR, the total strain is thirty percent greater for the case with traction than the test without. The developed test seems to load the sensitive area in tensile, thus promoting the crack initiation.

However, it was demonstrated that mechanical loading of the sheet is not the only parameter affecting hot cracking initiation. Metallurgy plays an important role especially during solidification.

Experimental results

In situ study

High speed camera recordings of the mushy zone during welding were made, in order to observe crack initiation. Mushy zone observation is complicated by the oxide formed at the weld pool surface. With an improved gas protection, the weld pool boundary appears (figure 8), and observation of the mushy zone is possible. In-situ observations permit a better understanding of the hot tearing initiation concerning solid fractions and dendrite morphology.

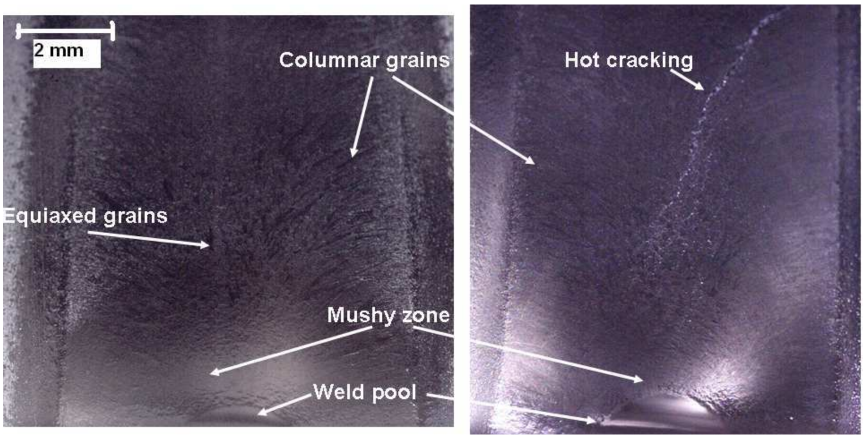

Fig.8. Video recording image during welding showing the weld pool tail.

Two areas with distinct granular structure can be generally observed on the in-situ recording, in the re-solidified zone: a columnar dendritic zone on the edge of fusion zone, and an equiaxe dendritic zone in the center. However, at the lowest speed welding, the fusion zone is composed entirely of columnar dendritic grains. Some theoretical considerations can explain these results. The formation of an equiaxe dendritic zone is promoted by the undercooling degree in the border between fusion zone and mushy zone. Undercooling is favored by high solidification speed and low thermal gradient [3]. At high welding speed, solidification rate is high, but thermal gradient is too high on the edges of the fusion zone to create an equiaxe zone. So a columnar grains structure growing perpendicularly to the isothermal surfaces is formed. The thermal gradient is lower in the center of the fusion zone, which explains the germination of equiaxe grains in this zone. Moreover, when reducing the distance between fusion line and specimen border, an asymmetry of the fusion zone structure appear. The columnar zone is then shorter in the border sample side. This can be explained by a lower thermal gradient on this side, because heat conduction in metal is reduced due to the sample border proximity.

Observation with high speed camera confirms that cracks initiate in the columnar zone, in a direction transverse to the welding direction. As a result, and depending on welding parameters, the cracks stop or bifurcation in longitudinal cracks propagation are observed in the equiaxe zone.

Post-mortem study of cracks morphology

After welding, the samples are cut out to obtain cross sections views. The microstructure is studied using a combination of several technical: conventional optical microscope, macroscopie, and scanning electron microscope.

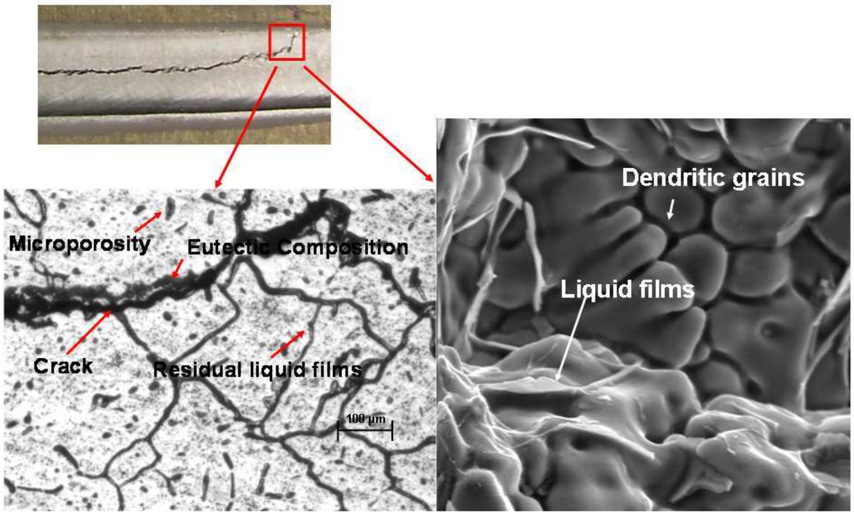

Fig.9. Observation of cracks: (a) macrograph top view, (b) micrograph in transverse section, (c) SEM fracture.

Microscopic observations of cracked areas (figure 9b), clearly show inter granular cracks resulting from a debonding of liquid films. Indeed, the coalescence solid fraction, corresponding to the lower boundary of the BTR is reached first between two dendrites of the same grain, and then between two grains, which promotes the initiation of inter granular cracks rather than intra granular. The presence of liquid films at the solidification end is visible on the fracture surfaces studied by scanning electron microscope (figure 9c).

The microstructure observation revealed a very characteristic grain structure, with peripheral columnar grains, oriented in a direction perpendicular to the welding direction, and a central equiaxe zone, for our welding conditions [5,6]. The zones width depends on the welding parameters that vary, namely, with current and speed welding. Hot tearing sensitivity is also correlated to the grain morphology in the mushy zone. It is generally admitted that columnar dendrite morphology, with dendrites growing in the thermal gradient direction, generally observed for rather low solidification speed and/or high thermal gradient [3], is more sensitive than equiaxe dendric morphology. This can be understood by the fact that the liquid feeding between the equiaxe grains is facilitated even at the solidification end, as well as the crack healing phenomenon by liquid feeding. It has been confirmed with these observations that for most of the samples, the crack initiation occurs between the dendritic columnar grains, on the weld pool edges.

This is not a surprising result, because this area combines an unfavorable microstructure, and the higher strain level, as shown in previous section. The longitudinal tensile preload applied during the test also favors transverse cracking between columnar grains.

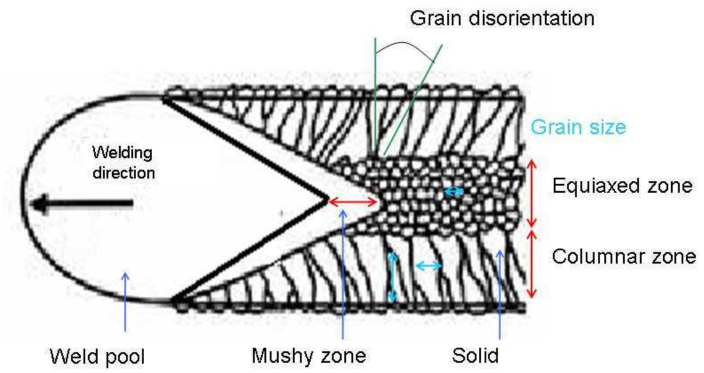

Fig.10. Microstructural characteristics.

Microstructural analyses also allow to characterize the morphology of fusion zone, according to quantitative parameters, like the grain shape and size, the growth direction, the disorientation between grains (figure10) related to welding parameters, that can reflect a sensitivity to cracking. For instance, a central line emergence at columnar dendritic grains junction increases hot cracking sensibility, according to Hunziker [7]. If the thermal conditions leading to the formation of various grain morphologies are well known, the relationship between welding parameters and microstructure is less well explained, because of the complex relationships between these parameters and temperature fields generated.

On average, for our tests, a columnar dendritic zone about 1,5 mm on each side and an equiaxe dendritic zone about 2 mm are found. However, the proportion of each grain morphology zone is a function of welding parameters. A correlation between the relative size of these zones and the crack propagation can be seen. When the equiaxe width zone is small compared to the total width of the cord, crack will tend to spread more easily in a large longitudinal crack. Moreover, when the fusion line is shifted closer to one edge, the crack always initiates from that side. A thermal asymmetry is then created in the weld bead.

In our case, the columnar grains growth direction is characterized by an angle of 80 degrees relative to the welding direction. The grain orientation also affects the ability possessed by the liquid to supply the material lack. Wang showed the importance of disorientation between two grains [8]. This disorientation also limits the liquid supply at the dendrites foot, limiting the cracks healing. The maximum disorientation found on our tests is about 22 degrees. However, cracks initiation does not occur where the grains are highly disoriented between them in our case. The distance between arc initiation and first crack initiation appears rather constant, between 2 and 4 cm.

Influence of process parameters

The results of this first test campaign enable the classification of welding parameters as cracking or not cracking conditions for a given tensile pre stress. Figure 11 shows the crack sensitivity evolution of 6061 alloy as a function of welding parameters. After welding, the cracks formed were first revealed by penetrant testing. The results highlight several failure modes, depending on process parameters, figure 11. For high welding speed, some small transverse cracks are observed at the beginning of the welding line at the weld edges, which deviate rapidly to propagate in a large longitudinal crack (width of 0.6 mm on average). However, when speeds are lower, there is a succession of fine transverse cracks (less than 30 µm in width) that do not reach the central equiaxe zone. For each welding speed range studied, except the lowest, there is a critical welding current from which the cracking is observed.

It can be observed that large longitudinal cracks are only observed for high welding speed. However, low welding speed promotes columnar grains structure, which is more sensitive than equiaxe structure. This indicates that in our tests, mechanical effects, resulting from the evolution of stress and strain fields on the preloaded and clamped sample subjected to a local heating are more important than microstructural effects.

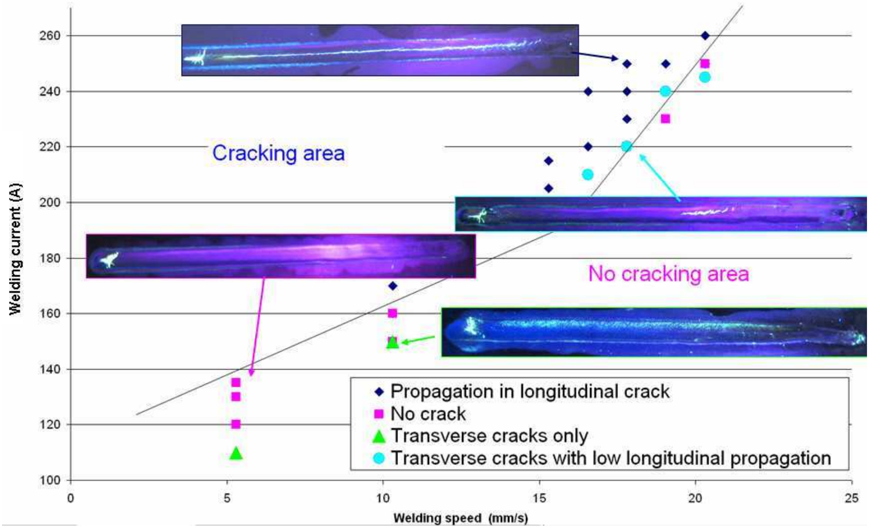

Fig.11. Hot cracking map with penetrant testing results.

RDG criterion

To complete this study based on pre-loading influence on hot cracking initiation, the crack initiation criterion developed by Rappaz, Drezet, Gremaud (RDG criterion) [9] has been used to compare hot cracking sensitivity. This criterion is applied as post processing of finite elements calculations presented before. The RDG criterion, based on the calculation of a critical depression $\Delta P_{\max}$ on dendrites foot requires the total strain rate of the solid skeleton perpendicular to the grain growth direction and the liquid ability to flow between grains calculated using Carman Kozeny permeability model developed for porous media. The formulas for calculating this depression are presented below (1, 2). μ and β correspond respectively to liquid viscosity and to solidification contraction coefficient. The temperature T, the temperature gradients G(T), the total strain rate $\dot{\varepsilon}_P(T)$ and the solidification speed v_T are deduced from the numerical simulation of the welding test made in parallel to experimental investigations.

$$\Delta P_{max} = \frac{180.(1+\beta).\mu}{\lambda_2^2}\int_{T_S}^{T_L}\frac{E(T).f_s(T)^2}{(1-f_s(T))^3.G(T)}dT + \frac{180.v_T.\beta.\mu}{\lambda_2^2}\int_{T_S}^{T_L}\frac{f_s(T)^2}{(1-f_s(T))^2.G(T)}dT \quad (1)$$

$$E(T) = \frac{1}{G(T)}\int_{T_S}^{T} f_s(T).\dot{\varepsilon}_P(T)dT$$

The characteristic lengths λ_2 (spaces between the secondary dendrite arms) were extracted by micrographs. The evolution of the solid fraction fs(T) is calculated using Scheil-Gulliver relation. The pressure evolution, calculated along dentrictics columnar grains, is shown on figure 12.

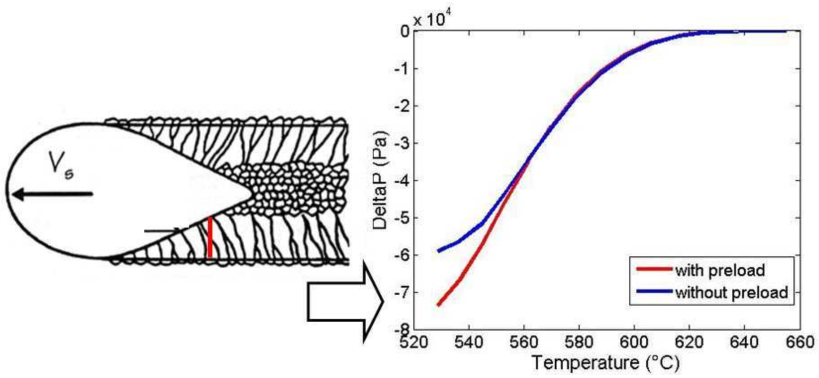

Fig.12. Results of RDG criterion.

The depression is greatest at the weld edge, near the dendrite foot. Depression is more important for the test with traction than the test without. This first criteria observation seems to confirm the influence of the tensile preload in the welding direction on the hot cracking sensitivity. The depression value will then connect to the welding parameters in order to highlight the metallurgical, process and mechanics interactions.

Conclusion

It has been demonstrated that solidification cracking is a faceted problem, with many influencing parameters. A lot of studies examine hot tearing but few have studied the relationship between mechanical aspect induced by process and microstructure. A new, original and simple test has been developed to promote hot cracking initiation. To apply a tensile preload on the welding direction seems to promote the crack initiation for our welding conditions. Knowledge of mechanical loading imposed allows us to work on the interaction between material and process. Cracking phenomenon is the correlation of sensitive microstructure and critical mechanical loading. Thus, cracking begins, for all our welding conditions that we tested, in the peripheral zone, which has a columnar grain structure, while the central zone of equiaxed structure is more resistant to the phenomenon.

Observation using high speed camera will better understand the mechanisms of crack initiation and bifurcation at the grain scale. Moreover, the mapping representing the field cracking based on welding conditions shows the importance of welding power on the crack initiation and the different failure types. The microstructure characteristic lengths measured have been introduced in the RDG criterion in order to introduce microstructural parameters in hot cracking sensitivity.

New tests will be accomplished by varying the tensile preload in order to deepen the cracks initiation conditions in welding. In order to optimize the process, localized heating study can help change thermal loading [10] and therefore the microstructure of critical zone. These changes will also occur on mechanical loading of the mushy zone thus revealing importance of structural effect on crack initiation.

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