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Hot-crack test for aluminium alloys welds using TIG process

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Abstract. Welding is an assembling process highly used in industry. Because of current market requirements, manufacturers push welding processes up to their limits: increasing productivity, reducing costs as well as ensuring welding assemblies quality. However, increasing welding speed causes many defects such as hot cracking (also known as hot tearing or solidification cracking). It is one of these defects which strongly affect weld quality and mechanical strength. The aim of this study is to link up the emergence of hot tearing with characteristic length of material by means of different measures.

1 Hot cracking in welds : state of art

Aluminium alloys are highly sensitive to hot tearing phenomenon. It appears during solidification of the alloy, so it can be observed during welding, as well as during casting or other processes involving solidification. During welding, components are subjected to high thermal gradients around the melting zone due to localized heat input. Solidification area, located at the rear of the melting zone, corresponds to a "mushy zone" where liquid and solid phases coexist. When solidification speed is not too high, the mushy zone is ranged between two isotherm surfaces corresponding to liquidus and solidus temperatures. However, for high solidification speed, the temperature range of the mushy zone is moved due to undercooling [3].

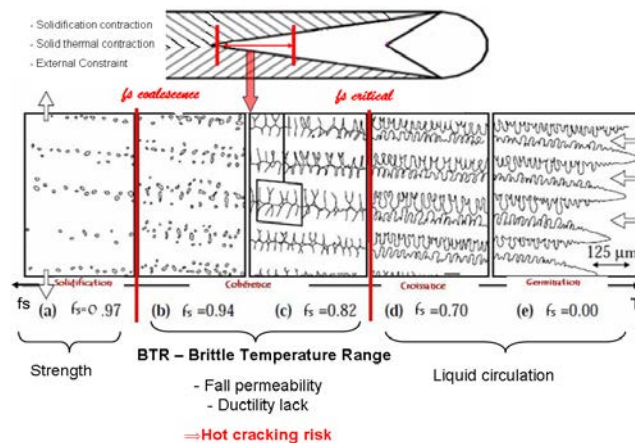


Fig. 1. Evolution of the microstructure of the mushy zone as a function of temperature.

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Hot tearing phenomenon is generally associated to a lack of ductility of the mushy zone when liquid fraction becomes too low. The material sensitivity to hot tearing can then be characterized by the ductility into a "Brittle Temperature Range" (BTR) corresponding to the interval between the "coherency temperature", where the liquid does not easily circulate because of the low permeability of the solid skeleton, and the "coalescence temperature", where the solid opposes mechanical resistance (Figure 1) [6].

However, the 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 low solidification speed and/or high thermal gradient [2], is more sensitive than equiaxed dendrite morphology. Hot tearing appears when the mushy zone is subjected to strain and stress fields. In welding, the mechanical loading is primarily produced by thermal strains due to temperature evolution around and in the mushy zone. High speed cooling after welding implies a solidification shrinkage (due to phase change) and thermal contraction of the solid skeleton (which depends on the expansion coefficient of the solid already formed). Added to these thermal strains, external clamping stresses can prevent the natural distortion. All these stresses can cause decohesion of liquid films, initiating the cracks.

Various hot tearing tests have been developed in order to study the alloys sensitivity [1]. They can be classified in two families: the self-clamping tests, where the mechanical loading of the mushy zone is produced by the thermal restraint of a bulk sample, and the external load test, like the Varestraint test, where a plastic strain is induced by a loading device during welding of the sample. These tests allow classifying alloys according to their sensitivity but do not develop quantitative criteria for each material.

The purpose of the present work is to study interaction between mechanical and metallurgical factors in order to better identify the parameters leading to hot tearing during welding. Originality of this study is to try distinguishing structural effects on a global scale in the face of microstructural effects on a local scale. An original test developed for hot tearing characterization in welding is first presented. Next, experimental results achieved in arc welding on a 6061 aluminium alloy are analyzed.

2 The experimental system

A simple original hot tearing test for thin plates has been developed in this study. The originality of this test is to apply a controlled tensile pre-stress along welding direction on a rectangular sample cut on thin aluminium plates of 0.8 to 3 mm thicknesses (figure 2). An automatic Gas Tungsten Arc Welding (GTAW) process has been chosen for these tests. With this process, electrical arc is created between a tungsten refractory electrode and the sample, in an inert gas, generally argon, to protect metal against oxidation.

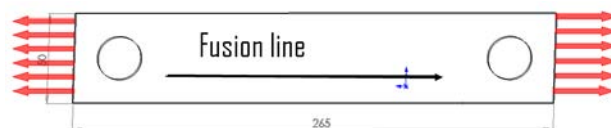


Fig. 2. Longitudinal tensile specimen with TIG fusion line.

During welding, the specimen is clamped on both sides between two jaws. A fusion line is made with GTAW process on the aluminium sample along the longitudinal direction. A shift of the fusion line from the sample symmetry plane to one sample side (figure 2), or change of tensile pre-stress value, allow investigation of structural effects on hot tearing. The advantage of this test, compared to other hot tearing tests such as Varestraint test [1], is its simplicity which is interesting for an industrial use. In addition, the simple sample geometry and boundary conditions make easy 2D numerical simulation of the test.

Hot tearing test is placed on a mobile two axes (X, Y) table, figure 3. During a welding test, welding arc is in a fixed position and the sample is translated in the longitudinal direction at constant speed. In that way, observation of the weld pool with high speed camera is possible all along the test. With this test, microstructure control 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 controlled by welding parameters adjustments, by the pre-stress applied thanks to the clamping system, and by the distance from the border sample to the fusion line. The present test then allows distinguishing between structural effects on a global scale and microstructural effects on a local scale.

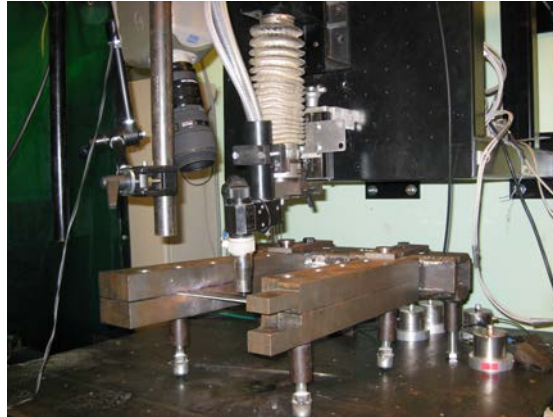


Fig. 3. Two axes table with hot tearing test.

A first test campaign was achieved in order to validate experimental device. 6061 alloy specimens, of dimensions $265 \times 50 \text{ mm}^2$ were water jet machined from 2.3 mm thick plates. During all these tests, a 200 MPa preload is applied. High welding speeds in the range 5 mm/s - 20 mm/s, and 130 A - 260 A current range were chosen for this first campaign. For each welding speed, current range are chosen to have a fully penetrated welding pool on the plate. A 3 mm arc length is imposed for all the welding tests, which corresponds to a welding voltage of about 10 V.

3 Experimental results

3.1 In situ study

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 surface. With an improved gas protection, the weld pool liquidus boundary appears (figure 4), and observation of the mushy zone is possible. We expect of these in-situ observations a better understanding of the hot tearing initiation concerning solid fractions and dendrite morphology.

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 equiaxed 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 equiaxed dendritic zone is promoted by the undercooling degree in the border between fusion zone and mushy zone. Undercooling is favoured by high solidification speed and low thermal gradient [2]. At high welding speed, solidification speed is high, but thermal gradient is too high on the edges of the fusion zone

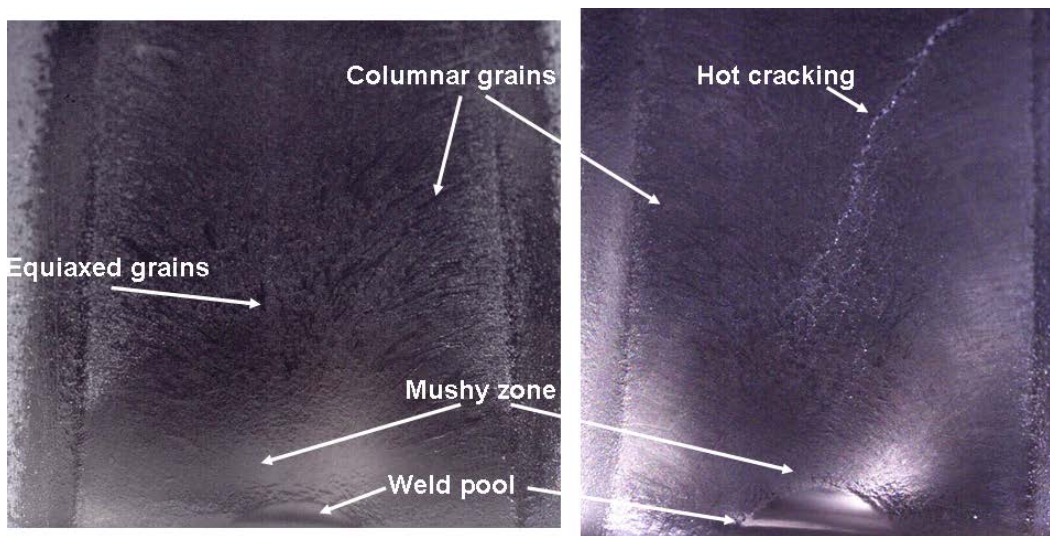


Fig. 4. Video recording image during welding showing the weld pool tail

to create a equiaxe zone. So a columnar grains structure growing perpendicularly to the isothermal surfaces is formed. The thermal gradient is lower in the centre 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, we notice an asymmetry of the fusion zone structure. 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 also shows that cracks initiate in the columnar zone, in a direction transverse to the welding direction. As a result, and depending on welding parameters, we observe the cracks stop in the equiaxe zone, or a bifurcation and a longitudinal cracks propagation, in the equiaxe grains zone.

3.2 Post-mortem study of cracks morphology

After welding, the formed cracks where first revealed by penetrant testing. The results highlight several failure modes, depending on process parameters, figure 5a). For high welding speed, some small transverse cracks are observed at the beginning of the welding line at the edges of the weld, which deviate rapidly to propagate in a large longitudinal crack (5a)). Conversely, for low welding speed, the observed transverse cracks are more numerous, and do not deviate in a longitudinal direction.

Post mortem observations of the samples after welding at higher magnification allow to better analysing the hot tearing mechanism. It has been confirmed with these observations that for most of the samples, the crack initiation occurs between the dendritic columnar grains. It is well known in literature that dendritic columnar grains are more sensitive to hot tearing than equiaxe dendrites [3]. The columnar grains are more sensitive to hot cracking, because the liquid flow up to the bottom of the columnar dendrites is much more difficult than between equiaxe grains. Thus the liquid can not come close the material lack, due to the solidification shrinkage, at the dendrite foot, we will have crack appearance. In addition, the longitudinal tensile preload applied favours transverse cracking between columnar grains.

Microstructural analyses also allow to characterize the morphology of the fusion zone, according to quantitative parameters, like the grain shape and size, there growth direction, the disorientation between grains, related to welding parameters, figure 6, that can reflect a sensitivity to cracking. For instance, a central line emergence of columnar dendritic grains junction increases hot cracking sensibility, according to Hunziker [3].

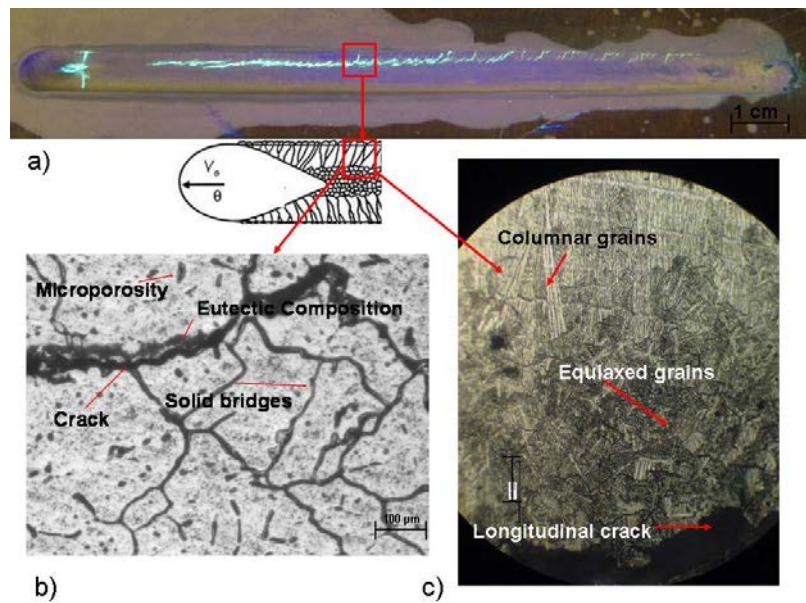


Fig. 5. a) Penetrant testing in a cracked specimen, b) Hot crack micrograph formed during welding of 6061 alloy (x 100) , c) columnar and equiaxed zones formed during welding of 6061 alloy.

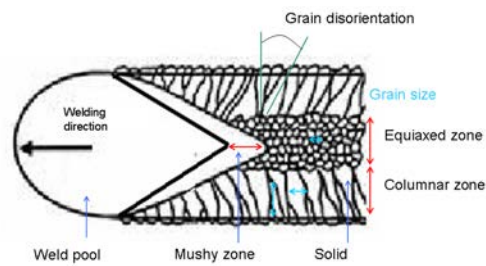


Fig. 6. Microstructural characteristics

For our welding conditions, the central line is never observed, except for the lowest welding speed. At high welding speeds, interaction thermal / metallurgical microstructure gives a dendritic columnar grains on the bath edge and equiaxed in the cord center. Proportion of each one of the two zones is a function of welding parameters. On average, in cracking tests, we find a columnar dendritic zone about 1,5 mm on each side and a equiaxed dendritic zone about 2 mm. The crack initiation width is about 30 microns. The width after propagation is an average of 200 microns along the center line. The proportion of each grain morphology is a function of welding parameters. When the equiaxed 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 created in the weld bead. The disorientation between grains does not seem a crucial parameter on the crack initiation location, because angle between grain does not exceed 15° . The distance between arc initiation and first crack initiation appears constant and between 2 and 4 cm.

Micrograph observations of cracks indicates a interdendritic fracture, typical of the hot tearing phenomenon figure 5b).

3.3 Influence of process parameters

The results of this first test campaign allow classifying welding parameters as cracking or not cracking conditions for a given tensile pre stress. Figure 7 shows the crack sensitivity evolution of 6061 alloy as a function of welding parameters.

It can be observed that large longitudinal cracks are only observed for high welding speed. However, low welding speed promotes columnar grains structure, which are more sensitive than equiaxed 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.

At high welding speed, cracking appears when the welding current reaches a critical value, depending on the welding speed. The understanding of the effect of the welding current on the hot tearing phenomenon is difficult, because it requires knowing the effect of this parameter on the strain and stress field in the sample. In order to better understand these effects, a numerical simulation of the welding test will be achieved, in parallel to experimental investigations.

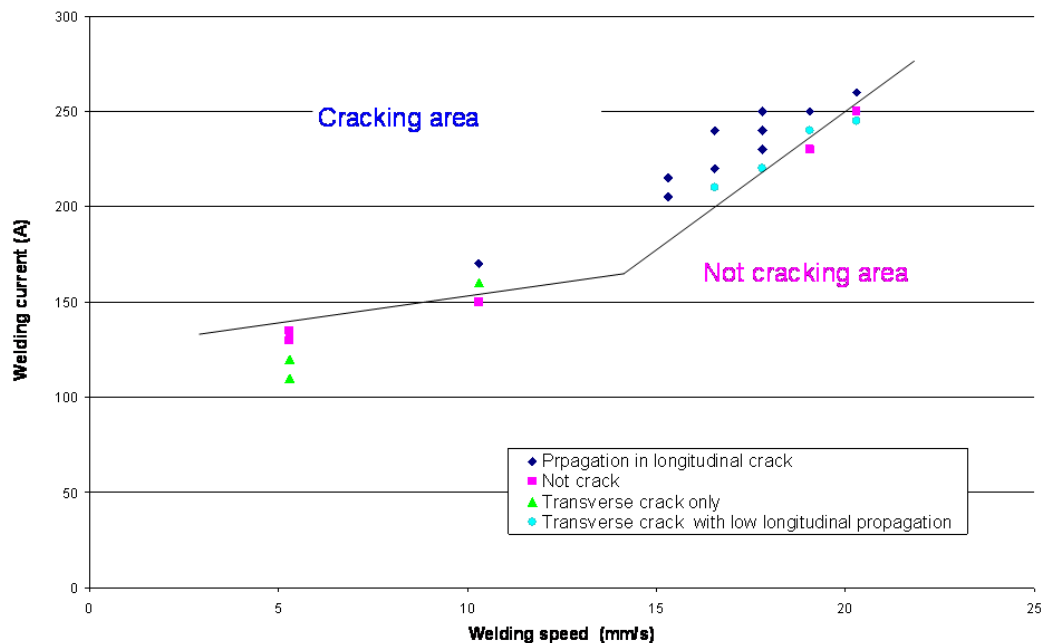


Fig. 7. Hot cracking map.

4 Conclusion

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 due to welding parameters and pre-stress applied.

Observation using high speed camera will better understand the mechanisms of crack initiation and also a bifurcation at the grain scale. Moreover, the mapping representing the field cracking based on welding conditions used to evaluate the importance of energy welding on the crack initiation. The measures have shown different mode crack propagation of the thermal loading. In our welding conditions, microstructure composed of equiaxed zone and a columnar zone is conducive to crack

initiation. The characteristics lengths measured will be introduced as influencing parameters of crack sensitivity.

A criterion for crack initiation is then developed. It will consider deformation speed, permeability but also microstructure. This criterion will be applied in post processing with modeling results of developed test.

In order to optimize the process, localized heating study can help change thermal loading and therefore the microstructure of critical zone . These changes also will occur on mechanical loading of the mushy zone thus revealing importance of structural effect on crack initiation.

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