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MICROSTRUCTURE GENERATION DURING CuNi BEAD ON PLATE: COMPARISON OF EXPERIMENTAL RESULTS AND CA PREDICTION

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ABSTRACT

Controlling the microstructure of welds is important to assess the structural integrity of joint. The microstructure is controlled by different factors such as heat and mass transfer occurring in the weld pool. Different parameters as welding speed and current waveform lead to different microstructure morphologies. Experimental tests with different parameters were conducted on CuNi plate with in situ observation around the solidifying interface to evaluate the microstructure evolution. This setup allows to observe and to investigate the dendritic growth around the semi-solid zone. Some EBSD maps were performed for different process parameters and are used for comparison. To model microstructure generation, cellular automaton (CA) have proven its versatility. It can model complex phenomena of solidification such as grain growth, grain competition, nucleation and Columnar to Equiaxed Transition. One of the main ingredient to model the microstructure morphology is the dendritic growth model that is linked to the undercooling. The objective of this paper is to compare experimental results with some cellular automaton results and to discuss the modelling of dendritic growth model under different solidification conditions.

INTRODUCTION

Microstructure prediction is important to assess or enhance mechanical integrity of welded joint. Solidification microstructure generation during welding can be predicted by different models taking into account thermal field along the solidifying zone in the rear of the weld pool. In the prediction, thermal gradient (G) and front velocity (V) driven by the process can be used to predict the columnar to equiaxed transition [1]. To take into account microstructural effect such as the dendritic growth, cellular automaton can been used. By coupling thermo-hydraulic simulation of the process with cellular automaton, the influence of process parameters on the microstructure generation during different welding processes can be investigated [2]. Despite the interest for welder, cellular automaton suffers from the

complex behaviour of industrial alloy during solidification. In this paper, some bead on plate experiments with a binary alloy with a precise known composition are reported. The experimental results based on a simple academic test can be used for comparison with cellular automaton modelling. In particular, the influence of process parameters on microstructure generation can be analysed by a simple two dimensional model. The article is divided in two parts. The first is focused on experimental investigation [3] done around the solidifying zone. The other is on process and microstructural modelling. The comparison gives important information on the influence of process parameters on microstructure generation.

EXPERIMENTAL RESULTS

EXPERIMENTAL SETUP AND MATERIAL

Simple bead on plate is done with a Gas Tungsten Arc Welding. The setup was developed to observe solidification at the back side with a high speed camera. To prevent any oxidation on the weld pool a chamber full of Argon is on the other side of the torch. Specimens are 1.6 mm thickness, 100 mm wide and 200 mm long. A bead is realized in the middle of the plate and the plate is clamped all along the side. The arc voltage is around 10V and the arc current is kept at 90A. The two welding speeds are given in table 1. The welding speed are modified in order to modify the geometry of the weld pool and to modify the solidification rate. The change in welding speed will also influence the fluid flow velocities inside the weld pool. The difference of heat distribution will lead to different microstructure.
The material to investigate the relation between process parameter (welding speed) and microstructure generation is CuNi binary alloy. This alloy has a relative simple phase diagram.

Table 1 Process parameters

Experiment	Arc current (A)	Arc voltage (V)	Welding speed (mm/s)
300J/mm	90	10	3
210J/mm	90	10	4,3

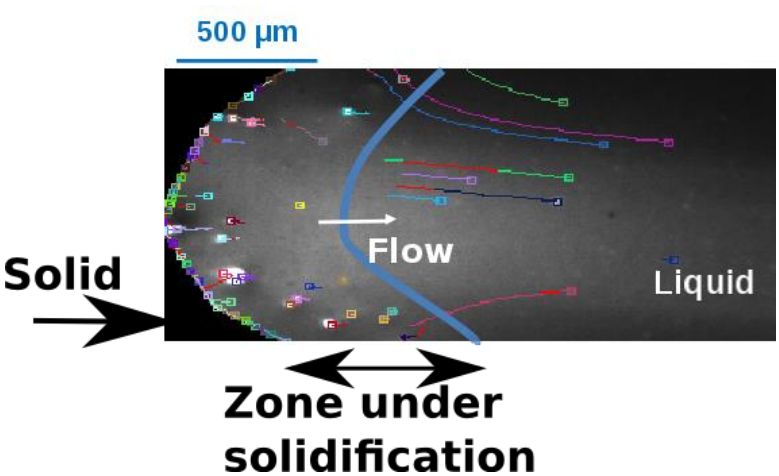

Fig. 1 Image acquired with a high speed camera on the back side of the solidification zone. Particles are used to estimate the velocity flow.

In figure 1, a small region of interest in the rear of the weld pool is observed with a high speed camera. The purpose was to understand the main phenomena appearing during solidification. Particle can be used to estimate fluid flow velocities. The detection of particle position show that on the back of the weld pool, the flow gets out of the zone under solidification and that the fluid velocities are around 160 mm/s against a solidification rate around 3mm/s.

EXPERIMENTAL RESULTS

After bead on plate, coupons were cut and EBSD were realized on specimen 300 J/mm and 210 J/mm. The two EBSD maps of the fusion zone are shown on figure 2. It is clear that the higher is the energy by unit length, the wider is the weld bead and the larger is the grain size. The different colours are proportional to the crystallographic direction of the grain. Because most of the further analysis is plane, the crystallographic direction [100] will be assumed to be in the plane (X, Y) and will be noted [10]. It can be seen that the grain are more tilted with lower welding speed. EBSD results gives a 20 micrometres for the initial grain size of the base material.

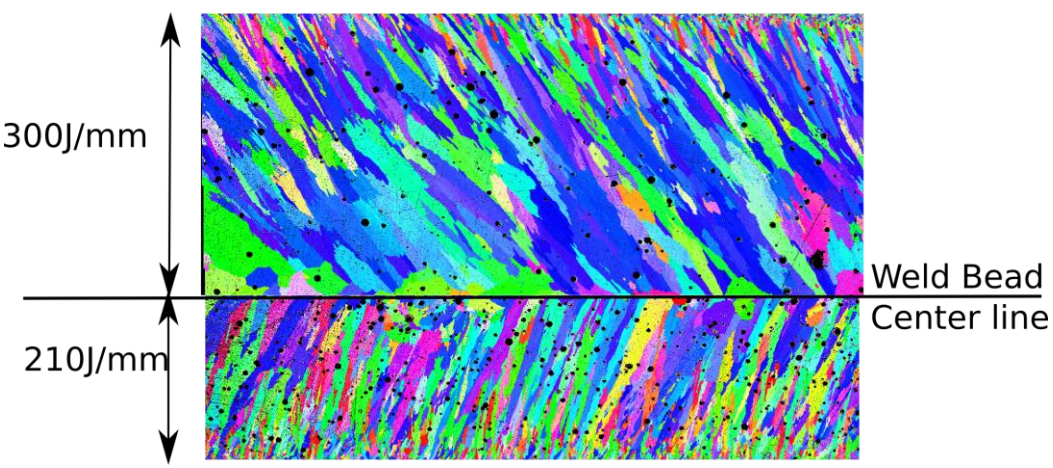

Fig. 2 EBSD (Y direction is horizontal) for the two tests used for comparison. Black disks correspond to porosities. The length of the specimens are around 10mm. Blue colour is correspond to [111] direction in Y direction.

In figure 2, EBSD analysis gives the crystallographic direction of the grain. For the two energies, small grains are visible. This is typical from the epitaxy phenomena from the border. Then for the two EBSD maps, it can be seen that grain growth competition takes place and then longer grain dominates with a preferential orientation. With the same crystallographic direction at each pixel, the geometry of a grain can be extracted. Based on this geometry, grain area and principal direction of the grain can be computed. In figure 3,

the grain geometrical principal orientations are plotted. The figure 3 shows that more the energy by unit length is high more the grains are oriented in the direction of the welding direction.

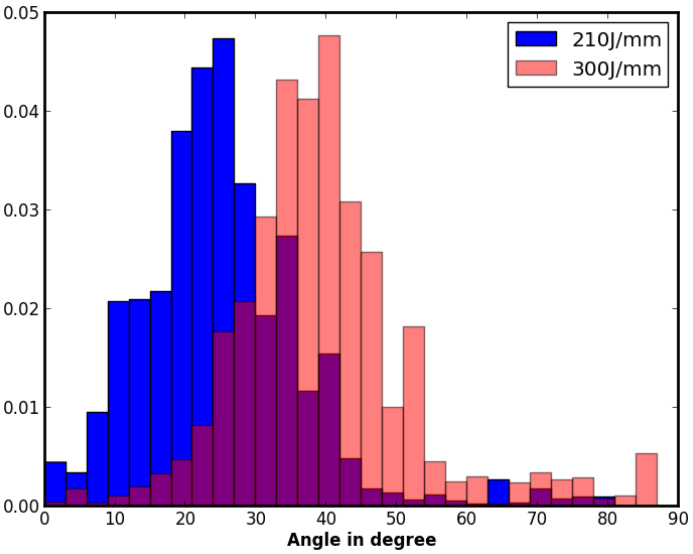

Fig. 3 Grain principal direction in the fusion zone. 300J/mm has grain tilted to 45 degree with respect to the weld direction whereas the other is only around 20 degrees. The orientation are weighted by the size of each grain.

MODELLING

PROCESS MODELLING

The process is modelled with finite element thermal modelling. The model is purely thermal conduction. The plate is modelled in plane problem. The heat is assumed to be equally distributed along the thickness. The plate is clamped on the side. The interaction between the arc and the plate is modelled by cylindrical volumetric Gaussian heat source:

$$q_v = \frac{3\eta U I}{\pi R_0^2 e} e^{-3\left(\frac{(X-X_0)^2+(Y-Y_0-V_s t)^2}{R_0^2}\right)}$$

where U is the arc voltage, I the arc current, Xo and Yo are the initial position of the torch and Vs is the welding speed. Ro is a radius to pass the most of the electric energy in a disk of radius Ro and η is the efficiency to convert electric energy to thermal energy. To take into account better heat transfer inside the weld pool, the conductivity is artificially increased by

a factor around 10. Two thermocouples and the weld pool size are used to identify the efficiency η that can vary from test to test due to different thermal effect. To take into account thermal effect due to clamping, a convection exchange is taken into account and is set to 30.10^{-3} W/mm^2. The material parameters are given in table 2.

Table 2 Thermal material parameters of CuNi

Coefficient	Value	Unit
Solid state Conductivity	0,04	W/mm/K
Density x Capacity	0,0047	J/mm3/K

The two sets of parameters used in experiments are used for simulation to investigate the influence of process parameters on solidification. To conclude numerical simulation parameter Ro is set to 3mm and the efficiency is taken to 0.92 for 300 J/mm and 0.87 for 210 J/mm.

SOLIDIFICATION

Solidification phenomena are modelled within a cellular automaton (CA). Due to complete penetration, a two dimensional CA model is used. Details of CA implementation can be found in [2, 4] for welding. For this study, no nucleation mechanism is taken into account. Dendritic growth is model as a classical KGT model and can be assumed to have the following form:

$$v_g = f(\Delta T) = A\Delta T^n$$

where Delta T is the undercooling and A and n are two parameters related to the material and the behaviour during solidification tab.3). The kinetic growth of the dendrite tip is the important ingredient for the microstructure prediction.
The microstructure of the base material is generated with a mesh of around 0,08mm in the region of interest. This grain size is larger than experimental one but the purpose is to investigate the relationship between process parameters and modification of microstructure. Each node of the mesh is a centre of a Voronoi cell representing a grain. All numerical tests will be done with the same initial microstructure.

Table 3 Set of parameters for KGT

Parameter	Value
A	0,00001
n	2

NUMERICAL RESULTS

The results of CA computation based on the thermal simulation of the process are shown in figure 4.

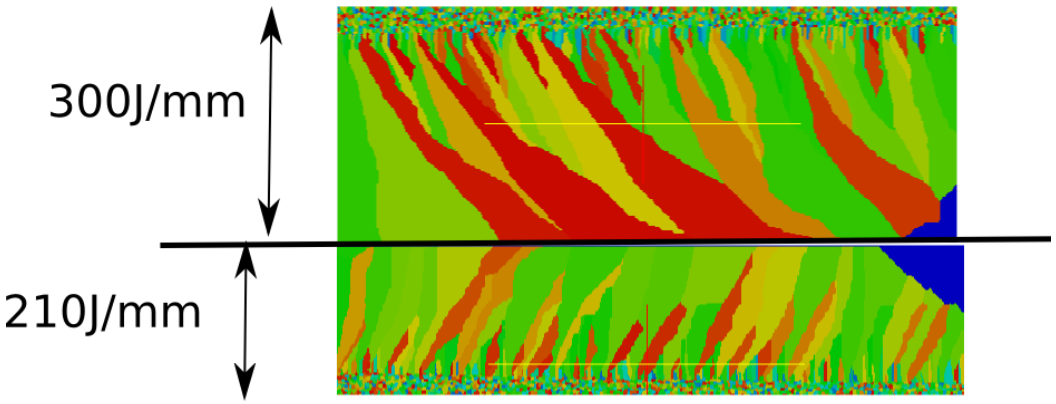

Fig. 4 Morphology of grains in the weld bead. The colour of each grain correspond to the orientation of [10] [01] frame in the X, Y frame. Red colour correspond to $\pi/4$ and green correspond to 0 degree. The length of the result is around 12mm.

For the two tests, two zones can be distinguished. One zone is near the weld bead border. It corresponds to the epitaxy phenomena where there is a competition of small grains of the base material. Once the grain selection had occurred, the grain growth occurs in the second zone. In figure 4, it can be seen that grains are smaller and straighter with a higher welding speed. This fact confirms the experimental observation, figure 1. The CA computation for 300J/mm shows that the [10] crystallographic direction is tilted of 45 degrees relative to the X, Y frame. Grains in the CA computation are larger than the experimental one. Nevertheless, if grains geometry principal direction are extracted and plotted in manner similar to figure 2, the figure 5 is obtained. In figure 5, it can be seen that the principal direction (geometry and not crystal orientation) of the grain are in agreement with the one observed with EBSD maps.

DISCUSSIONS

The prediction of microstructure based on thermal process simulation followed by a cellular automaton gives the same tendencies as the microstructure observed during experimental tests. It seems that grain size obtained during the experiments are smaller than the one predicted. It can come from two possible differences between the modelling and the experimental tests. The first is due to initial grain size in the base material. In the modelling

due to computation cost, an initial grain size four times larger was taken into account. Then the time of grain growth computation is smaller than for smaller than if smaller grain size were taken into account. The second difference can be attributed to the estimation of the thermal field during the process simulation. Our model does not take into account the influence of fluid velocity even if it is important in particular near the interface. If fluid flow is taken into account the gradient and the temperature field will be different and the growth kinetic due to undercooling will be modified. In the same kind of remark, the model is mainly two dimensional whereas the different phenomena are three dimensional. In particular, the appearance of grains for 300J/mm specimen in the middle of the weld pool can be attributed to three dimensional effects or a non-homogeneous thermal field induced by fluid flow.

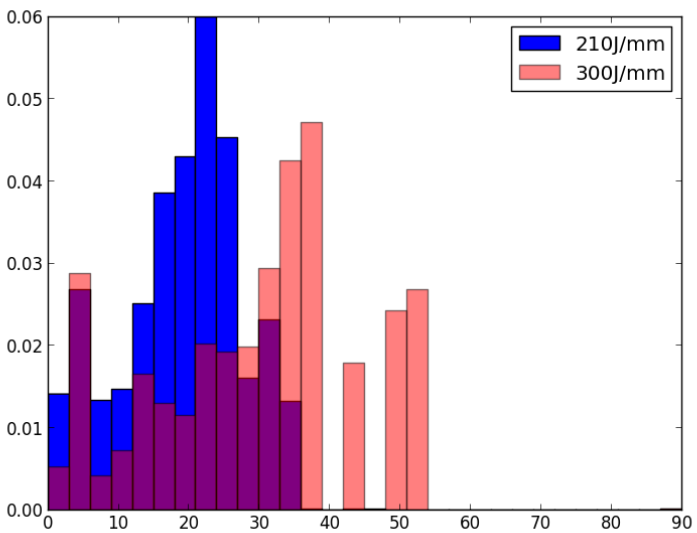

Fig 5 Grain principal direction obtained from CA computation based on thermal process simulation.

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