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ScienceDirect
Acta Materialia 82 (2015) 491–502
Acta MATERIALIA
www.elsevier.com/locate/actamat

Prediction of solidification cracking in pulsed laser welding of 2024 aluminum alloy

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Received 5 July 2014; revised 24 August 2014; accepted 1 September 2014
Available online 23 October 2014

Abstract—Laser welding of aluminum alloys can be associated with solidification cracking. The severity of cracking in these alloys depends on various factors, such as the initial temperature of the base metal and the temporal amplitude of the laser pulse. The purpose of this investigation is to understand this correlation, and thus to put forward a criterion for solidification cracking in laser welding of 2024 aluminum alloy. The criterion for cracking is devised based on a modification of the existing criteria, to account for non-steady conditions, and interpreted with respect to the loci of the relevant isotherms and the length of the vulnerable zone in the melt pool, during the solidification stage. Based on this criterion and the respective experimental observations, it is demonstrated that welding with suitable ramping down of the laser pulse can lead to the elimination of solidification cracking in the examined alloy.

Keywords: Welding; Aluminum alloy; Laser treatment; Hot cracking criteria; Modeling

1. Introduction

Pulsed laser welding has potential for application to heat-treatable aluminum alloys, due to the nature of the process and high accuracy in process control. On the other hand, solidification cracking continues to be one of the major challenges in the application of fusion welding to joining aluminum alloys [1–3]. There are reports, for instance, that some aluminum alloys can be welded without solidification cracking only under certain laser pulse conditions [4,5].

Solidification cracks initiate in the mushy zone during the last stage of solidification as a result of shrinkage, thermal stress/strains, hindered contraction and lack of liquid feeding. Because of the nature of the mushy zone and complex interactions of the above mechanisms, the prediction of solidification cracks is a complicated subject. Many studies have been performed on establishing hot cracking mechanisms and identification of the governing factors [6–17]. As a result, various criteria have been proposed for hot cracking. However, most of them concern casting processes, which have significantly different time and length scales as compared to laser welding. Most of the proposed criteria are based on either the non-mechanical aspects or the mechanical aspects, while a few combine the two.

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The hot cracking susceptibility (HCS) coefficient proposed by Clyne & Davies [6,7] is defined as the ratio of the susceptible time and the time available for backfilling or the stress-relief process. In Feurer's criterion [8,10–11], cracking is related to the difficulties of backfilling of the terminal liquid phase through the mushy zone in competition with solidification shrinkage. In Katgerman's criterion [9–11] the theoretical considerations of Clyne & Davies and Feurer are combined.

The applications of these criteria in the prediction of hot tearing behavior in direct chill casting have been investigated by Suyitno et al. [11]. It is shown that Feurer's criterion and Katgerman's criterion are able to predict the cracking sensitivity as a function of casting velocity and also location; the highest sensitivity at higher velocity and at the billet center. However, the positive effect of the ramping procedure (a lower casting speed during start-up phase) could not be anticipated by either criterion. It was shown, moreover, that Clyne & Davies' criterion was not able to correctly predict the effects of casting velocity and of ramping procedure on cracking susceptibility [11].

In this study, cracking severity is determined experimentally in pulsed laser welding of 2024 aluminum alloy, with a focus on the effect of the initial temperature of the base metal. In the analysis, the suitability of three criteria for the prediction of the condition for solidification cracking is assessed. These criteria include those proposed previously by Feurer, Clyne & Davies and Katgerman [6–9], for comparison. A new criterion is proposed based on Feurer's, which is originally for steady-state conditions. This

http://dx.doi.org/10.1016/j.actamat.2014.09.002
1359-6462/

criterion is further developed in the current study to treat the highly transient conditions encountered in fusion welding, particularly when using laser. The input data required for the analysis, including thermal history, cooling rate, and the velocity of isotherms, are obtained through numerical simulation. To complement the analysis, the present study includes experimental results reported by previous researchers on single pulsed laser welding and GTAW processes [4,5].

2. Methods

2.1. Theory

Feurer's criterion [8,10–11] is based on the assumption of a dendritic growth of the solid phase and a constant cooling rate, i.e. steady-state condition. Feurer proposed that solidification cracking occurs when liquid feeding rate of metal becomes less than solidification shrinkage rate. Just above the coherency temperature, the liquid still available between the solid cells is continuous and can move easily since the solid arms have not yet coalesced and compensate the deformation induced by shrinkage and thermal stresses. Thus, regions with temperatures lower than the coherency temperature are generally considered as vulnerable to cracking.

Two terms, *SPV* and *SRG*, were defined by Feurer. The first represents the maximum volumetric flow rate per unit volume (backfilling term) and the second is the volumetric solidification shrinkage caused by the difference between the density of solid and liquid phases. *SPV* is formulated as follows:

$$SPV = \frac{f_l^2 \lambda_2^2 \left(P_o + \bar{\rho} g h - \frac{4\gamma_{SL}}{\lambda_2}\right)}{24\pi c^3 \eta L^2} \quad (1)$$

with

$$\bar{\rho} = \rho_l f_l + \rho_S f_S \quad (2)$$

where f_l and f_s are volume fractions of liquid and solid in the mushy zone, respectively; λ_2 is the secondary dendrite arm spacing; c is the tortuosity constant of the dendrite network; η is the viscosity of the liquid phase; g is the gravity constant; $\bar{\rho}$ is the average density of the mushy zone; ρ_s, ρ_l are the densities of liquid and solid, respectively; and P_0 is atmospheric pressure. Also L is the length of porous zone. The shrinkage velocity (*SRG*) can be obtained as follows:

$$SRG = \left(\frac{\partial \ln V}{\partial t}\right) = \frac{(\rho_o - \rho_S + bkC_l) \cdot \dot{T} \cdot f_l^{(2-k)}}{\bar{\rho}(1-k) m_l C_0} \quad (3)$$

where ρ_0 is the density of liquid aluminum at the melting temperature; b is the composition coefficient of liquid density; C_l is the composition of the liquid at the solid–liquid interface; C_0 is the alloy composition; k is the equilibrium distribution coefficient; m_l is the slope of the liquidus; and $\dot{T}$ is the cooling rate during solidification of the primary solid phase. Based on this criterion solidification cracking occurs when *SRG* exceeds *SPV*.

As mentioned earlier, Feurer's criterion is based on the assumption of the steady-state growth condition, constant vulnerable zone length, constant cooling rate and a dendritic microstructure. However, pulsed laser welding is a non-steady process and the vulnerable zone length is profoundly variable during solidification. Moreover, metallographic investigations of the pulsed laser welded samples for each and every set of process parameters indicate a cellular structure, instead of dendritic [4]. Thus, as a modification to Feurer's criterion, to make it applicable to laser melting, it is necessary (a) to consider a cellular microstructure and (b) to take vulnerable zone length variations into account. For this reason as will be explained, vulnerable zone length will be considered as a time-dependent variable.

Fig. 1 illustrates the differences between fluid flow in cellular and dendritic microstructures schematically. In order to calculate *SPV* for a cellular structure, the equations have to be rewritten. Parameters used in calculations are shown in Fig. 1b. Thus, *SPV* is deduced as a function of primary dendrite arm spacing. It is supposed that solidification direction is parallel to the "z" direction in Cartesian coordinates and the "x–y" plane is perpendicular to the solidification direction. If it is assumed that liquid moves only along the "z" axis (the columnar grain direction), *SPV* can be related to one directional liquid velocity $v_{l,z}$ by

$$\frac{v_l}{V} = \frac{v_{l,z} \cdot A}{L \cdot A} = \frac{v_{l,z}}{L} \quad (4)$$

where L is vulnerable zone length. A is the cross-sectional area of vulnerable zone in the "x–y" plane and V is the corresponding volume. To calculate the cracking susceptibility at any region in the weld pool, one point should be selected in the corresponding region: for instance, in this investigation this point will be identified as "a". For point "a" (Fig. 1b) the vulnerable zone length is the distance between this point and the upper boundary of the vulnerable zone in the z direction ($L = L_a$). During the solidification, $L_a = 0$ when the temperature of point "a" (T_a) reaches the coherency temperature (T_{coh}) and with proceeding of solidification, this length increases and the maximum value will be achieved, i.e. when T_a will be equal to the effective solidus temperature (T_S). The liquid velocity in Eq. (1) can be calculated from Darcy's law [20,21]:

$$f_l \cdot v_{l,z} = -\frac{K}{\eta}\frac{\Delta P}{\Delta z} \quad (5)$$

where K is the permeability of the mushy zone. The right-hand side of Eq. (5) can be considered for the whole length of the vulnerable zone ($\Delta z = L_a$). ΔP is the pressure difference between the coherency point and the root of cells. The pressure drop in the mushy zone gives rise to the plastic deformation in the vulnerable zone. It is reported that the maximum induced deformation acting over the vulnerable zone originates from the restricted shrinkage/contraction of the alloy and can be estimated by thermal strains [18,19]. Based on rheological behavior of semisolids, the strain rate can in turn be related to stress by the creep law as follow rate [22]:

$$\sigma = \sigma_0 \exp(\alpha f_s) \cdot \exp\left(\frac{mQ}{\Re T}\right)(\dot{\varepsilon})^m \quad (6)$$

where Q is the activation energy, T is the absolute temperature, $\dot{\varepsilon}$ is strain rate, m is the strain rate sensitivity coefficient, α and σ_0 are material constants and $\Re$ is the gas constant. These are reported for an Al–Cu alloy as: $Q = 160$ kJ mol^{-1}, $m = 0.26$, $\alpha = 10.2$ and $\sigma_0 = 4.5$ Pa [22]. We assume that same values would be applicable to AA2024 alloy. ΔP was assumed to be equal to the stress obtained from Eq. (6) [21].