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TECHNICAL PAPER

Weld Solidification Cracking Behaviour of AA2195 Al–Cu–Li Alloy

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Abstract In this study, weld solidification cracking behaviour of AA2195 Al–Cu–Li alloy was studied and compared with conventional AA2219 and AA2014 aluminium alloys. Cracking susceptibility was evaluated using varestraint test and Gleeble® hot ductility test and the slope of liquidus temperature as function of liquid fraction was also evaluated. Solidification cracking susceptibility of AA2195, AA2219 and AA2014 alloys was ranked based on the above methods. Consistent trend in cracking susceptibility was observed in all the methods where AA2195 and AA2219 alloys showed highest and lowest cracking susceptibility, respectively.

Keywords AA2195 · Weld solidification cracking · Varestraint test · Gleeble® hot ductility test · Hot cracking

1 Introduction

AA2195 is an advanced Al–Cu–Li alloy used in propellant tanks of launch vehicle due to its high strength, low density and superior properties at cryogenic temperature. Fusion welding of this alloy is limited due to the solidification cracking phenomenon during welding. Various researchers have studied this phenomenon using different techniques such as varestraint test, Houldcroft test, circular patch test, Gleeble® hot ductility test [1, 2] for various aluminium alloys. Quantification of solidification cracking susceptibility for AA2195 alloy and its severity in comparison with conventional aluminium alloys (AA2219 AA2014) have not been studied earlier. In this study, solidification cracking susceptibility of AA2195 alloy was evaluated using varestraint test, Gleeble® hot ductility test and thermodynamic calculations. Cracking tendency of AA2195 alloy was compared with AA2219 and AA2014 alloys because all these alloys are Al–Cu-based system with copper as major alloying element. Also, AA2195 is a potential material to replace these conventional alloys in launch vehicle application.

2 Experimental Details

Chemical composition of Al alloys used is given in Table 1. AA2195 alloy was realized through vacuum induction melting (VIM) route using facility at M/s Midhani, Hyderabad and further forged and rolled to T87 temper condition.

In varestraint test, controlled external strain was applied in the weld pool during welding to generate the solidification cracks. Instantaneous strain was applied pneumatically using a die block of fixed radius once the welding arc reached the centre of the specimen. The schematic representation of varestraint test set-up and specimen are shown in Figs. 1 and 2, respectively. The augmented strain applied was related to the radius of die block and thickness of specimen as per the relation $\varepsilon = t/(2R + t)$ [1], where ε, augmented strain (%); t, thickness of the specimen; and R, radius of the die block. Die blocks with radius of 320, 160, 80 and 40 mm were used to obtain 0.5, 1.0, 2.0 and 4.0% of augmented strains, respectively. Maximum crack length (MCL) and total crack length (TCL) were measured from

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Table 1 Chemical composition of Al alloys

Material	Cu	Li	Mg	Zr	Ag	Si	Mn	Fe	Ti	V	Zn
AA2219	6.29	–	–	0.17	—	0.11	0.35	0.18	0.07	0.1	0.01
AA2014	4.47	–	0.4	0.05	–	0.75	0.58	0.23	0.05	0.03	0.07
AA2195	3.9	1.0	0.65	0.19	0.3	–	0.01	–	–	–	–

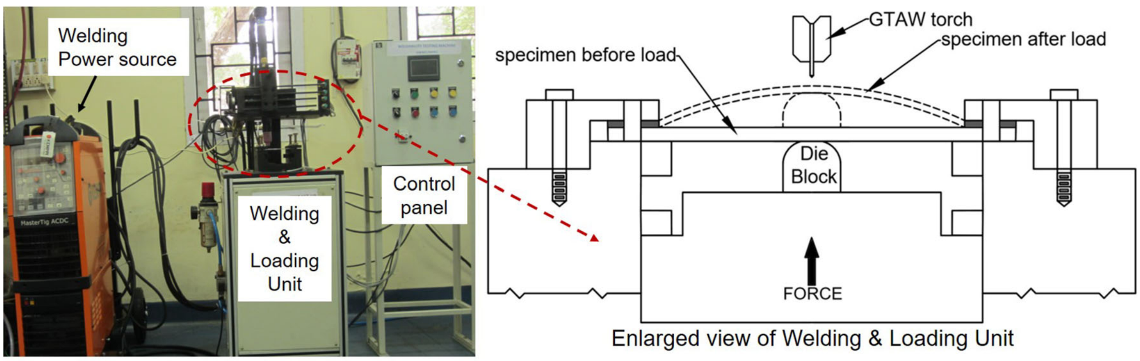

Fig. 1 Photograph and schematic representation of varestraint test set-up

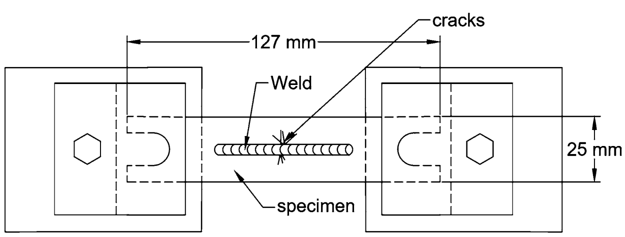

Fig. 2 Top view of varestraint test specimen loaded at machine

this test. Further, brittle temperature range (BTR) was derived from TCL and weld cooling rate.

In hot ductility test, solidification cracking susceptibility was measured using Gleeble® thermo-mechanical simulator. Critical temperatures such as “nil strength temperature” (NST), “nil ductility temperature” (NDT) and “ductility recovery temperature” (DRT) were measured for three alloys. Solidification cracking temperature (SCTR) which corresponds to cracking susceptibility was derived from NDT and DRT. NST is the temperature at which the strength of the material drops to zero. NST determination was an on-heating test; 8-kg constant load was applied before start of heating, and specimen was heated at the rate of 20 °C/s up to temperature below 100 °C of liquidus, then 1–2 °C/s until failure. Like NST, NDT determination is also an on-heating test, and the specimen was heated to specific test temperature and pulled at the speed of 50 mm/s. The temperature at which ductility of the material drops to zero is nil ductility temperature (NDT). DRT determination is an on-cooling test, wherein specimen was heated to NST and with no time of soaking, cooled to a test temperature and pulled until failure. Temperature at which 5% ductility recovered was noted as DRT.

Kou [5] modified the RGD criterion [4] to arrive at a simple hot cracking index that took into account phase diagram, solidification shrinkage, strain rate, cooling rate and liquid feeding. Curves of T versus $(f_S)^{1/2}$ Al alloys were plotted to find the maximum $|dT/d(f_S)^{1/2}|$ using Thermo-Calc® 4.1 software with database COST 507.

3 Results and Discussion

Weld solidification cracking occurs at the terminal stages of solidification. During that stage, there is a mismatch between the thermal stresses due to solidification shrinkage and the ability of the last liquid to fill in. AA2195 alloy of 4 mm thickness was welded using gas tungsten arc welding (GTAW) process, and solidification cracking was observed. Typical solidification cracking in AA2195 alloy is shown in Fig. 3. Width of the weld at crown and root side is 10 mm and 5 mm, respectively, and mean inter-dendritic spacing is measured as 12 µm.

Cracking susceptibility depends on amount and distribution of interdendritic eutectic phases and freezing range of the alloys. As the amount of eutectic phases is high and they are distributed continuously along the interdendritic region, it is made easy for solidification crack to propagate through this region. Similarly, if the freezing range is wider, low melting phases remain for longer time during

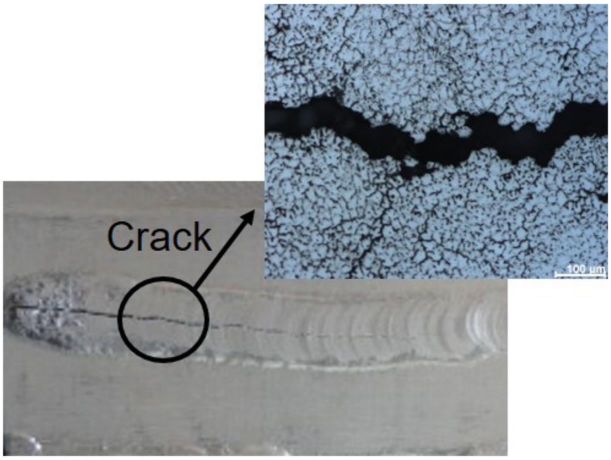

Fig. 3 Solidification cracking in 2195 alloy

solidification. These phases cannot accommodate the stresses generated during welding, thereby cracking occurs.

In varestraint test, experiments were conducted at 0.5, 1.0, 2.0 and 4.0% strain levels for all Al alloys. Solidification cracking increases with an increase in strain at all levels and in all three alloys. Total crack length (TCL) and maximum crack length (MCL) have been measured and plotted. Solidification cracking temperature range (SCTR) can be derived from weld cooling rate, welding speed and MCL using a relation SCTR = (cooling rate × MCL)/welding speed and is given in Table 2. TCL and MCL are found to be highest for AA2195 alloy and lowest for AA2219 at all four strain levels. Cracking susceptibility increases (as AA2219 < AA2014 < AA2195) as SCTR is increased (Fig. 4).

In hot ductility test, critical temperatures such as NST, NDT and DRT were determined using Gleeble® thermo-mechanical simulator. Brittle temperature range (BTR) is a critical temperature range that represents cracking susceptibility, and it is the temperature difference between NST and DRT [3]. Test results of various critical temperatures for all three alloys are given in Table 3. In AA2219 alloy, ductility is recovered in a narrow temperature range, whereas AA2195 shows poorer ductility recovery on cooling from NST. BTR measurement confirms that AA2195 alloy has poor cracking resistance than AA2219 and AA2014 alloys and the susceptibility trend is same as varestraint test.

SCTR from varestraint test and BTR from Gleeble® hot ductility test are critical temperature range for solidification cracking to occur. These temperature ranges are different from freezing range ($T_{\text{liquidus}} - T_{\text{Solidus}}$) of an alloy.

Kou et al. [5] stated maximum steepness $|dT/d(f_S)^{1/2}|$ as the solidification cracking index using thermodynamic software database. In their criteria, phase diagram, solidification shrinkage, strain rate, cooling rate and liquid feeding were considered. It was reported [5] that increasing $|dT/d(f_S)^{1/2}|$ near $(f_S)^{1/2} = 1$ increases the crack susceptibility by decreasing the grain growth rate dR/dt where grains bond together to resist cracking. It also increases the length of the liquid channel along the grain boundary. Longer the grain boundary channel, difficult for the liquid to fill the grain boundary and resist cracking. Therefore, $|dT/d(f_S)^{1/2}|$ near $(f_S)^{1/2} = 1$ was proposed as an index for the solidification cracking susceptibility.

Temperature (T) versus solid fraction $[(f_S)^{1/2}]$ has been plotted for Al alloys with an assumption of Scheil's solidification model of no diffusion. In this study, Thermo-Calc software has been used to plot T versus $(f_S)^{1/2}$. Maximum steepness $|dT/d(f_S)^{1/2}|$ values calculated for AA2219, AA2014 and AA2195 alloys are 1520 °C, 2323 °C and 2891 °C, respectively. Higher the slope towards the end of solidification, higher the cracking susceptibility and vice versa (Fig. 5).

From the above tests, it can be observed that trend of solidification cracking susceptibility is similar and it increases in the order of 2219 < 2014 < 2195. Cracking tendency is greatly influenced by amount, distribution and nature of eutectic phases formed and the critical solidification cracking temperature range.

4 Conclusions

Autogenous welding of AA2195 is prone to solidification cracking, and the crack susceptibility extent was studied using varestraint, Gleeble hot ductility test and Thermo-Calc software and compared with AA2219 and AA2014 alloys. In varestraint test, maximum crack length (MCL) and total crack length (TCL) were measured and

Table 2 MCL and SCTR values of aluminium alloys

Alloy	MCL (mm)	SCTR (°C)
AA2219	3.19	62
AA2014	4.62	92
AA2195	5.32	105

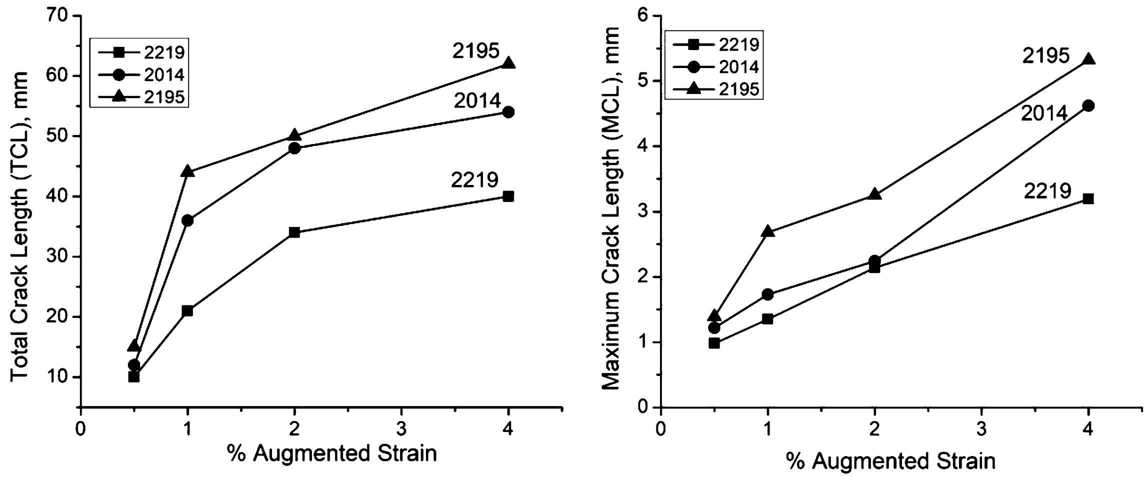

Fig. 4 MCL and SCTR values of aluminium alloys

Table 3 Critical temperatures obtained from Gleeble® hot ductility test

Alloy	NST (°C)	NDT (°C)	DRT (°C)	BTR (°C)
AA2219	588	535	526	62
AA2014	569	502	472	97
AA2195	601	533	475	126

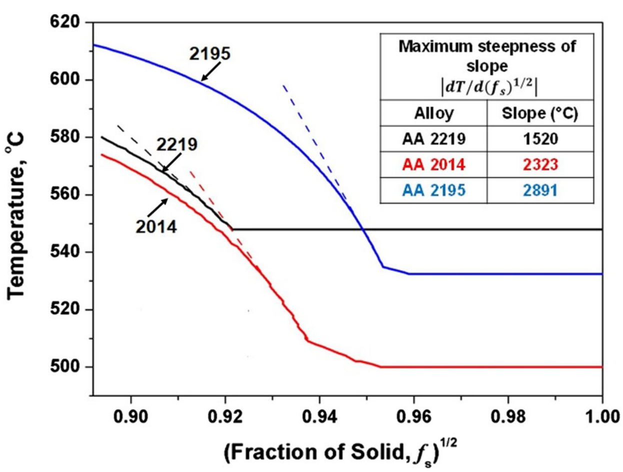

Fig. 5 Temperature (T) versus solid fraction [$(f_S)^{1/2}$] plot using Thermo-Calc software

solidification cracking temperature range (SCTR) was derived. At all strain levels, MCL, TCL and SCTR were highest for AA2195 alloy. In hot ductility test, AA2195 alloy showed narrow BTR which implied higher cracking susceptibility. In Thermo-Calc software simulation, maximum steepness $|dT/d(f_S)^{1/2}|$ was used as a solidification cracking index. Maximum steepness slope value for AA2195 alloy was found to be higher than other two alloys. In all the three tests, the trend of solidification cracking susceptibility was similar and it increased in the order of AA2219 < AA2014 < AA2195.

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