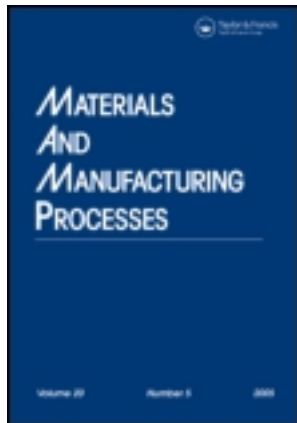


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## Materials and Manufacturing Processes

Publication details, including instructions for authors and subscription information:

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Accepted author version posted online: 31 Aug 2011. Published online: 03 May 2012.

To cite this article: C. C. Chang, C. L. Chen, J. Y. Wen, C. M. Cheng & C. P. Chou (2012) Characterization of Hot Cracking Due to Welding of High-Strength Aluminum Alloys, *Materials and Manufacturing Processes*, 27:6, 658-663, DOI: [10.1080/10426914.2011.593245](https://doi.org/10.1080/10426914.2011.593245)

To link to this article: <http://dx.doi.org/10.1080/10426914.2011.593245>

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# Characterization of Hot Cracking Due to Welding of High-Strength Aluminum Alloys

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The “Spot-Varestraint Test” was applied to assess the sensitivity of three aluminum alloys—A2024-T351, A2219-T87, and A7050-T6—to hot cracking from welding. The results indicate that the number of cracks increases with increasing augmented strain. This phenomenon occurs in both the fusion and the heat-affected zones. The number of thermal cycles also has a significant influence on the heat-affected zone; the number of hot cracks increases, especially in the heat-affected zone of the metal weld, with increasing number of thermal cycles. The compositions of these three alloys show that A2024 and A7050 have similar tendencies to be subject to hot cracking, greater than A2219. With increasing number of thermal cycles, the hot cracks show the same tendency, A2024 > A7050 > 2219.

*Keywords* Aluminum; Hot cracking; Thermal cycle; Varestraint.

## INTRODUCTION

The high strength aluminum alloys have been widely used as aircraft structural materials due to their specific set of characteristics, namely, high strength, good corrosion resistance, high resistance to repeated loads, and low rate of fatigue-crack propagation [1]. However, during welding, the area near the welding seam is influenced by the input energy. The material in this area has a property of becoming modified, similar to what occurs after heat treatment for a short period. These changes are evident in aluminum alloys of heat-treatment type. Types A2xxx and A7xxx belong to high-strength alloys with heat treatment that improves their hardness and strength. In general, an aging process and solid solution are used to enhance the material's mechanical properties [2]. However, few studies to compare with hot cracking characteristic on the three high-strength aerospace aluminum. Therefore, the motivation of this experiment is to study the sensitivity of hot cracking in high-strength heat treatment type aluminum alloys. This information is valuable to aircraft and military industries.

During the welding process, it is impossible to avoid some defects, such as induced cracks, deformation, porosity, and impurity. When the local stress of these defects that exists in the welding seam or the heat-affected zone (HAZ) is greater than the maximum stress of the substrate, cracks are induced from these defects. These cracks thus commonly appear in the area of high residual stress or a large concentration of stress,

such as the welding fusion zone (FZ) and the HAZ. Cracks generally arise in the welding process, and might cause serious problems. Aluminum alloys have large thermal expansion and large shrinkage, and therefore, a greater susceptibility to hot cracking. Much research has shown that several factors induce hot cracks in aluminum. In an aluminum alloy, the additional elements cause a widened range of solidification temperature; this is the major factor that causes a wide area of hot cracks [3, 4]. The content of these other elements in an aluminum alloy is the key factor to influence the sensitivity to hot cracking, such as 2.0–4.0% Cu, 2.0–5.0% Mg, 0.5–1.2% Si, 4.0–5.0% Zn, 1.5–2.5% Mn, and 1.0–1.5% Fe (all percentage by mass), that have a high possibility of inducing hot cracks [5–7]. The sensitivity to hot cracking attains a maximum, then decreases to a lower level with increasing content of one of these elements. The reason is that the eutectic liquid-type metal produces only a continuous thin film at the end of the solidification stage, so it can provide no extra eutectic liquid when hot cracks appear at the initial stage. The other way to decrease the sensitivity to hot cracking and thus to increase the weldability is to add a grain-refinement element, such as Zr, Ti, Sc [8–11]. There has been much research on aluminum hot cracking, and several methods have been devised to test the hot cracks, including the Varestraint test [12, 13], Fissure Bend, the Circular Patch test, the Houldcroft test [14, 15], the Hot Ductility test, and the Strain-Induced Crack Opening test [16, 17], of which the Varestraint test is the most popular method. The advantage of this method is that both welding parameters and stress can be varied independently, which is useful to investigate the metallurgical factors and mechanical properties on the material hot cracks.

Received April 12, 2011; Accepted May 6, 2011

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In this work, we used the “Spot-Varestraint Test” to study and compare the sensitivity of hot cracking of alloys A2024-T351, A2219-T87, and A7050-T6, under varied augmented strain and number of thermal cycles on the welding seams.

## METHOD

### Material Preparation

For this experiment we used commercially available aluminum plates A2024-T351, A2219-T87, and 7050-T6 as substrates. The size of substrate is length 200 mm × width 40 mm × thickness 3.0 mm. The chemical compositions are listed in Table 1. Before welding, the testing substrates were all cleaned chemically, according to the following procedures: soap and water cleaning → caustic cleaning (2 min) → clean water air-bubble bath (5 min) → acid solution cleaning (2 min) → clean water air-bubble bath (5 min) → ultrasonic oscillation cleaning with de-ionized water (2 min). After the above procedures were completed, the oxide layer was removed with a stainless-steel brush before welding.

### Welding Procedures

In these experiments we applied Gaseous Tungsten Arc Welding (GTAW) without an added feeder. Test specimens were prepared with the welding seam in the center. Samples with varied thermal cycles and with one or two welding energy inputs on the same welding seam were prepared, and are called Spot On Bead (SOB). These samples were used for further spot-welding strain experiments, as shown in Fig. 1(a). Table 2 shows the welding parameters for the welding seam on SOB.

### Spot-Varestraint Test

Figure 2 shows the Spot-Varestraint test machine; the sample is installed with one end fixed as a cantilever beam. The torch moves from left to right. When the torch reaches Point A as shown in Fig. 2, a pneumatically actuated loading yoke is applied, bending the sample to fit the surface curvature of the underneath removable die block. The torch moves concurrently at the same speed until reaching Point B.

The Varestraint test uses a cantilever mode to observe the induced cracks when a sudden strain is applied at the end of the welding process. The cracks surrounding the welding pool are measured by their quantity and lengths. The relation between these observed data and the stain determines the sensitivity

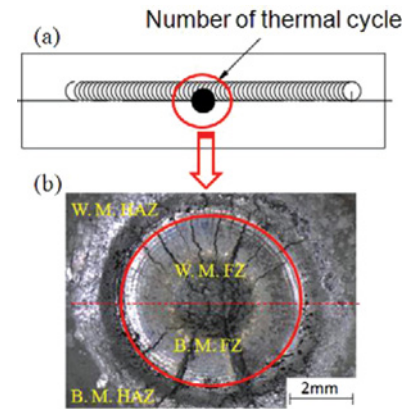


FIGURE 1.—(a) Spot welding and thermal cycles. (b) Hot cracks in weld metal FZ (W. M. FZ), HAZ (W. M. HAZ), and base metal FZ (B. M. FZ), HAZ (B. M. HAZ) (color figure available online).

to hot cracking. The augmented augmented-tangential strain,  $\varepsilon$ , is calculated with

$$\varepsilon(\%) = \frac{t}{2R} \times 100$$

in which  $t$  is the specimen thickness and  $R$  is the radius of curvature of the die block. The equipment for the Varestraint test can be used for hot cracking tests of varied types. This equipment is separable into three parts: a programmable welding device, a pneumatic actuator, and an electronic controller. As a programmable welding device, it is composed with one three-axis mechanical arm and its controller; this is integrated with the welder and implements a welding seam in both  $x$  and  $y$  directions with travel distance 160 mm in both directions. Together with the welding torch, it can implement welding seams in both longitudinal and transverse directions. The pneumatic actuator can be actuated with a maximum speed of 500 mm/s and stroke of 50 mm with resolution  $\pm 0.05$  mm; an electronic controller serves as a user interface to control both the mechanical arm and the pneumatic actuator. On following the setup operation steps and inputting the required parameters, Fig. 3 shows the actual experiment setup. The recipe for the Spot-Varestraint test is listed in Table 3

### Hot Cracking Analysis and Observation

After conducting the Varestraint test, the sample is placed on the observation stage of a microscope (Olympus SZX7) to observe the hot cracks in the fusion

TABLE 1.—Chemical composition of aluminum alloy, wt%.

	Mg	Si	Ti	Cr	Mn	Fe	Cu	Zn	Zr	Al
A2024-T351	1.47	0.34	0.08	0.019	0.61	0.28	4.43	0.059	—	Rem.
A2219-T87	—	0.2	0.06	—	0.35	0.3	6.48	0.04	0.175	Rem.
A7050-T6	2.11	0.07	0.03	—	0.03	0.08	2.05	6.14	0.11	Rem.

TABLE 2.—Parameters for welding.

Welding Current (A)	Welding Voltage (V)	Travel Speed (mm/min.)	Flow rate (L/min.)
125	5	250	15

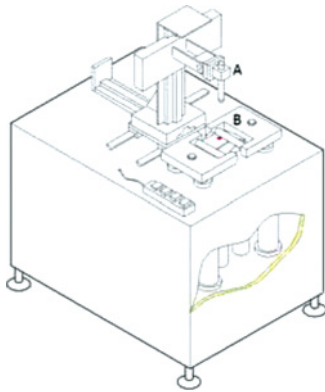


FIGURE 2.—Schematic graph of Sop-Varestraint test machine (color figure available online).

zone and the HAZ. From Fig. 1(b), software for computer image acquisition and analysis measurement are used to measure and to analyze the length of hot cracks in the fusion and the HAZ with varied augmented applied strains and thermal cycles. The total crack length (TCL) and maximum crack width (MCW) serve as three important indicators for evaluation of the sensitivity to hot cracking.

#### Microstructure Observation

To prepare the metallographic samples, a slow cutting machine was used to cut the observational section into cross-sections, and waterproof abrasive papers of types #1000 ~ #3000 were used in that order for polishing; then a flannel cloth was used with 0.1  $\mu\text{m}$  alumina polishing liquid for surface polishing. Finally, the test pieces were soaked in Kill's corrosive solution (HF (48%, 2 mL) + HCl (conc., 3 mL) + HNO<sub>3</sub> (conc., 5 mL) + H<sub>2</sub>O

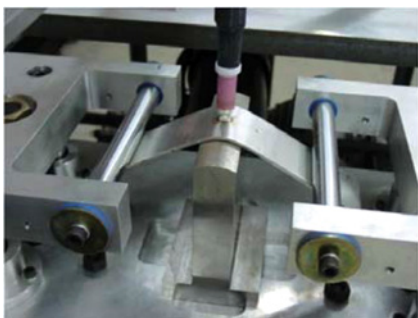


FIGURE 3.—Experiment setup for Spot-Varestraint test (color figure available online).

TABLE 3.—The welding parameters of spot-Varestraint test.

Welding Current (A)	Spot Time (Sec.)	Flow rate (L/min.)	Augmented-tangential strain $\epsilon$ (%)
125	5	15	2, 3, 5

(190 mL)) for 50–60 s, rinsed with large volumes of water, and dried rapidly. A metallographic microscope (OLYMPUS CX51M) was used to observe the morphology of the weld-beaded cross-section and the molten pool post-welding.

## RESULTS AND DISCUSSION

### Hot Cracking Sensitivity in the Fusion Zone

Figure 4(a–c) show the results of TCL in the fusion zone under varied augmented strain and thermal cycles

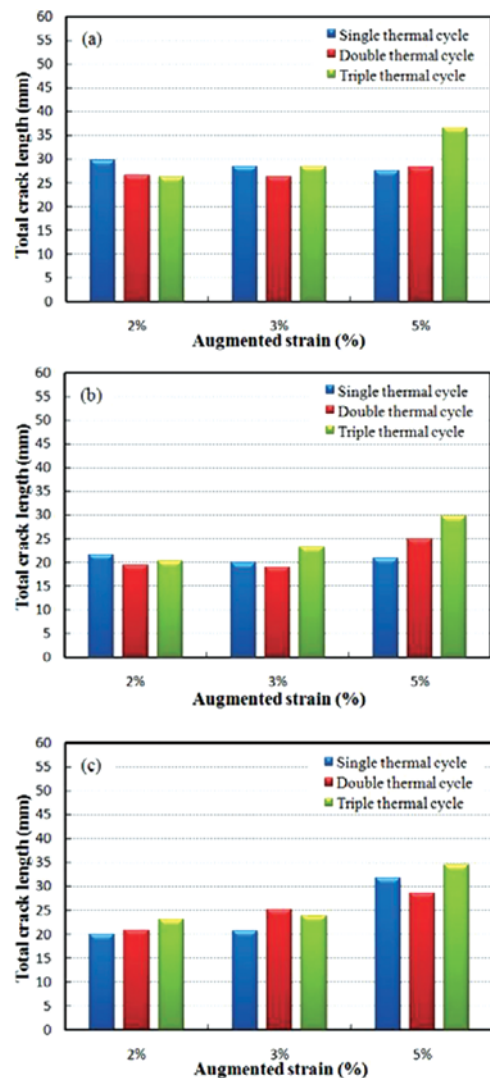


FIGURE 4.—Effect of total crack length in the fusion zone under varied augmented strain and thermal cycles: (a) 2024-T351; (b) 2219-T87; and (c) 7050-T6 (color figure available online).

for three aluminum alloys A2024-T351, A2219-T87, and A7050-T6, respectively. Under varied augmented strains, the results indicate that the TCL does not increase when the number of thermal cycles increases. After several thermal cycles, the TCL varies little in the base metal fusion zone (B. M. FZ) and weld metal fusion zone (W. M. FZ) in Fig. 3(b). The structure and composition thus do not change in the fusion zone after several thermal cycles. Figures 5(a,b) show metallographs of A2024-T351 after double and triple thermal cycles. It is difficult to distinguish the metallurgical microstructure from these two figures; the number of thermal cycles does not affect the sensitivity of hot cracking.

Figures 6(a–c) show the results of the MCW under varied augmented strains and numbers of thermal cycles for A2024-T351, A2219-T87, and A7050-T6 in the fusion zone. These experimental results show that the MCW increase when both the number of thermal cycles and the augmented strain increase. The main reason is the decreasing strengths of the weld and the HAZ causing the increasing augmented strain. The weld and the HAZ suffer from a larger stress and cause an increased MCW.

#### Sensitivity to Hot Cracking in the Heat-Affected Zone

Figures 7(a–c) show the results of the TCL in the HAZ under varied augmented strain and thermal cycles for the same three aluminum alloys, A2024-T351, A2219-T87, A7050-T6, respectively. The results show the TCL increases when the number of thermal cycles increases, but the TCL decreases rapidly when the augmented strain is 5%. The main reason is that the larger augmented strain causes the smaller segments of cracks to connect to larger ones. The overall TCL thus drops when the thermal cycles increase as shown in Fig. 6(a–c). The HAZ is determined in two parts: base-metal HAZ (B. M. HAZ) and weld-metal HAZ (W. M. HAZ). The experimental result shows that the hot cracks in the HAZ are located mostly in the weld metal HAZ, as shown in Fig. 1(b). Figure 7(a–c) indicate that the TCL of the hot cracks in the HAZ increases with increasing thermal cycles. Comparing the TCL in the base-metal HAZ and weld-metal HAZ, the weld-metal HAZ contributes more than the base-metal HAZ, because there is no tempering treatment during the welding process, and the weld-metal HAZ by spot

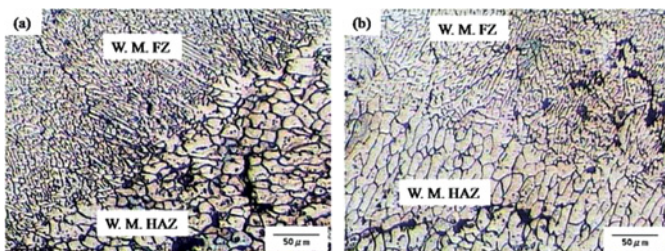


FIGURE 5.—Metallurgical microstructure for A2024-T351: (a) double thermal cycles and (b) triple thermal cycles (color figure available online).

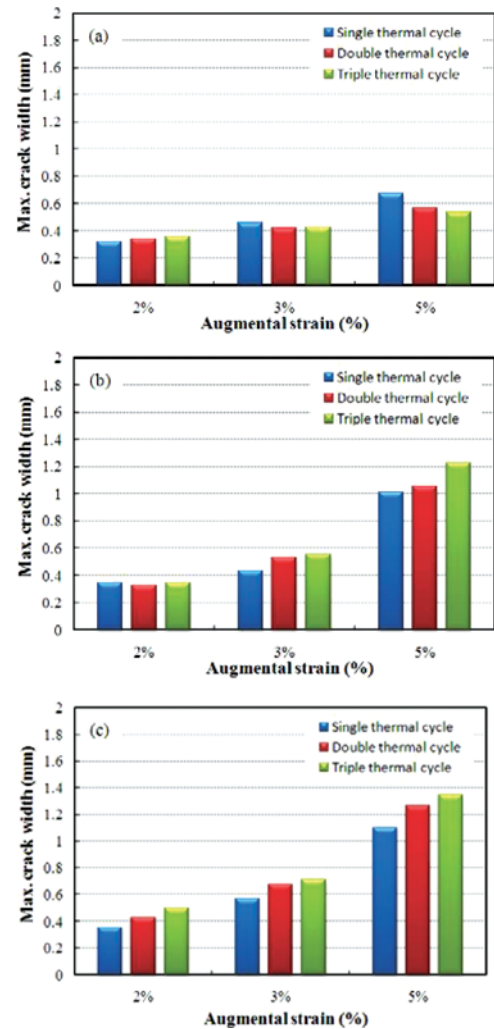


FIGURE 6.—Effect of maximum crack width in the fusion zone under varied augmented strain and thermal cycles: (a) 2024-T351; (b) 2219-T87; and (c) 7050-T6 (color figure available online).

welding would produce grain coarsening and precipitates at the grain boundary segregation [6].

#### The Effect of Augmented Strain on the Sensitivity to Hot Cracking

Figures 8(a–c) show the results of total crack length (TCL) under varied augmented strain and thermal cycles for three aluminum alloys, A2024-T351, A2219-T87, A7050-T6, respectively. The results show that the TCL increases when the number of thermal cycles increases. Due to greater augmented strain, the fusion zone and the HAZ suffer from larger stress, which causes the coherent interlocking solid network of the fusion zone formed during the final solidification and the melting grain boundary of the HAZ. The maximum strain took place perpendicular to the stress direction; most hot cracks were therefore found in the 6 and 12 o'clock positions. Fewer cracks were found in the direction parallel to the stress direction, shown in Fig. 1(b).

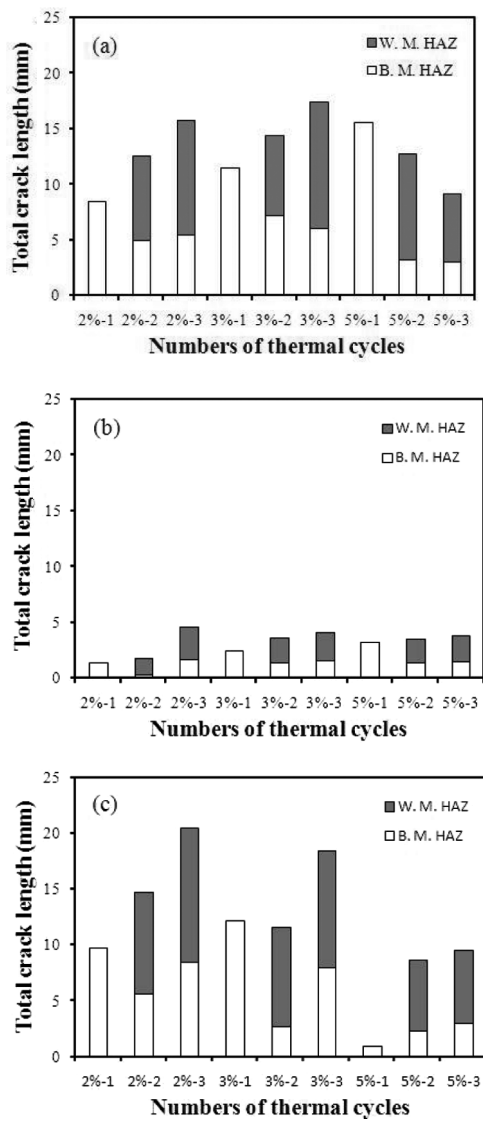


FIGURE 7.—Effect of total crack length in the heat-affected zone under varied augmented strain and thermal cycles: (a) 2024-T351; (b) 2219-T87; and (c) 7050-T6.

### Comparison of Sensitivity to Hot Cracking of the Various Materials

Figures 9(a–c) show the results of TCL under varied augmented strain and thermal cycles for various aluminum alloys. According to these results, the TCL of A2219-T87 is smaller than that of the other two alloys under the same number of thermal cycle with varied augmented strain. A2024-T351 has the greatest TCL. Compared with the material contents of the alloys, the 7050 series belong to the Al-Mg-Cu-Zn alloy type, and 2024 and 2219 belong to the Al-Cu alloy type; their copper content ratios are 4.43% and 6.48%, respectively. The content of copper in 2219 exceeds its maximum solid solution line in aluminum alloy, whereas the content of copper in 2024 is less than the maximum solid solution line [2]. The 2024 aluminum alloy consists of

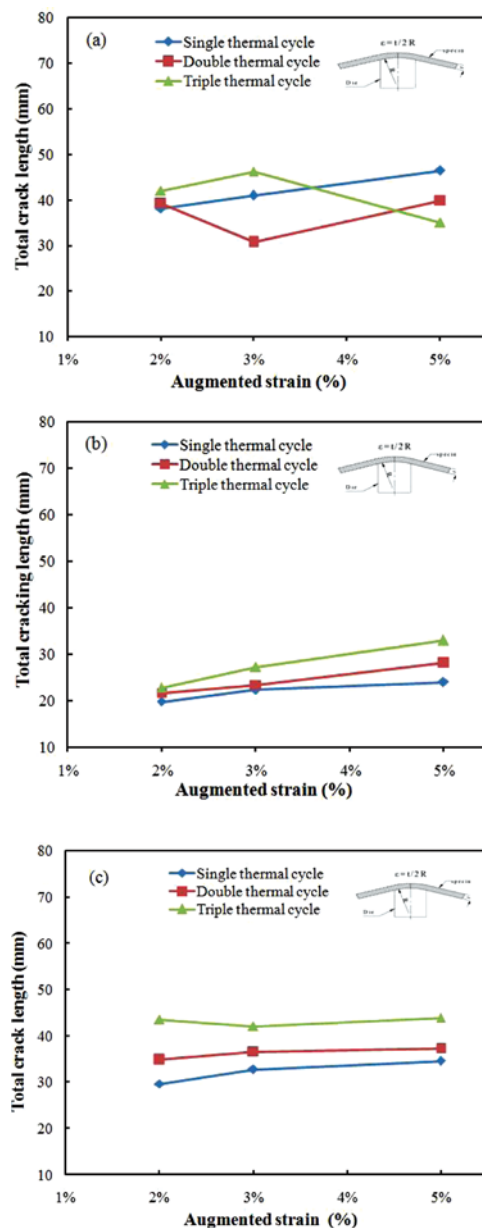


FIGURE 8.—Effect of augmented strain on the total length of hot cracks: (a) 2024-T351; (b) 2219-T87; and (c) 7050-T6 (color figure available online).

1.47% Mg that enhances the mechanical strength; the presence of Mg improves the ability of the solid solution to strengthen and the precipitation to strengthen. The composition of the aluminum alloy has a strong relation with hot cracks [3]. Cu, Mg, and Si play important roles. The contents Cu (2.0–4.0%), Mg (2.0–5.0%), and Si (0.5–1.2%) have the greatest sensitivity to hot cracking. When the composition of the aluminum alloy is near the above content ratios, it has an increased sensitivity to hot cracking. According to Table 1, the content elements in 2024 and 7050 show a greater sensitivity to hot cracking; they therefore both have greater sensitivity to hot cracking with varied thermal cycle.

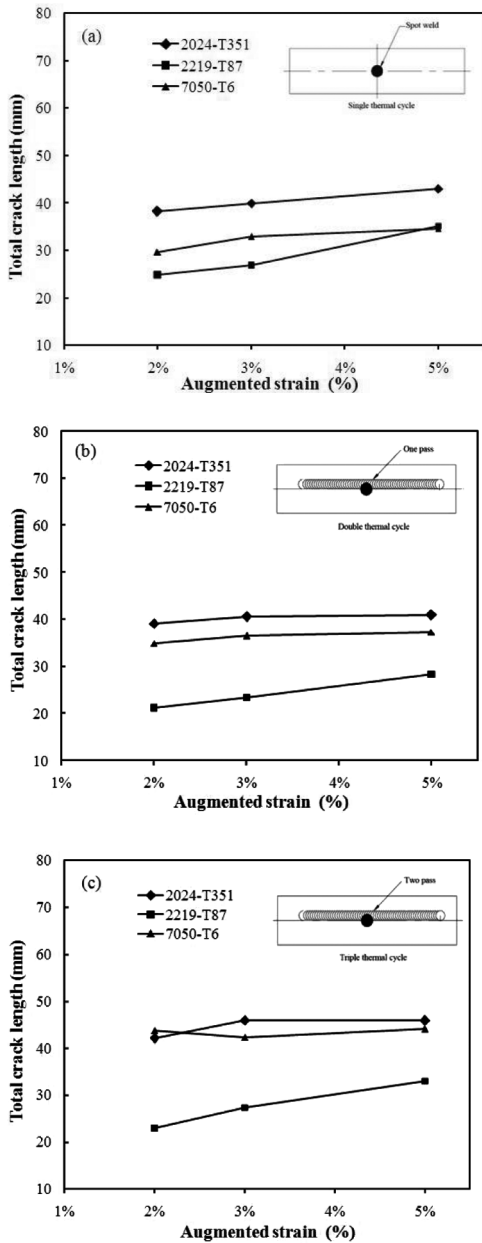


FIGURE 9.—Comparison of sensitivity to hot cracking of the various materials: (a) single thermal cycle; (b) double thermal cycle; and (c) triple thermal cycle.

CONCLUSIONS

The Spot-Varestraint test was used to analyze the sensitivity to hot cracking of three aluminum alloys—A2024-T351, A2219-T87, and A7050-T6—under varied augmented strain and thermal cycles. The experimental conditions and results can be summarized as follows. First of all, the number of thermal cycles does not influence the sensitivity to hot cracking in the fusion zone, but affects it significantly in the HAZ. The hot cracking increases when thermal cycles increase, especially in the HAZ. Secondly, the sensitivity to hot

cracking also increases in both the fusion and the HAZs, when augmented strain increases. Finally, 2024 and 7050 alloys have content ratios for inducing greater hot cracks greater than 2219. When the number of thermal cycles increase, the same results are produced, namely 2024 > 7050 > 2219.

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