Enhancement of mechanical properties of electron beam-welded D6ac steel tube

S. C. Wu[1], K. H. Tseng*[2] and H. C. Wen[3]

A forward flow-formed D6ac steel tube was joined through the electron beam welding process and was then subjected to post-weld heat treatment. The mechanical properties and hardness profiles of the as-welded (without heat treatment after welding) steel and different post-weld heat treatment weldments were investigated. The results show that the as-welded D6ac steel exhibited very poor mechanical strength and elongation. After post-weld heat treatment, a large improvement in the mechanical properties of the weldment was achieved. Forward flow-formed D6ac electron beam weldment subjected to post-weld heat treatment at 350°C reached the largest yield strength and ultimate tensile strength values (approximately 1359·2 and 1494·3 MPa, respectively). Forward flow-formed D6ac electron beam weldment subjected to post-weld heat treatment at a temperature of 650°C exhibited an overtempered state, which led to mechanical strength and hardness deteriorations of the weldment. This study found that the forward flow-formed D6ac electron beam weldment heat-treated at 350–450°C and held at this temperature range for 2 h exhibits high mechanical strength, sufficient elongation and a yield strength/ultimate tensile strength ratio of 0·91.

Keywords: D6ac steel, Forward flow forming, Electron beam welding, Post-weld heat treatment, Mechanical properties

Introduction

D6ac, a vacuum-melted, low-alloy steel containing several hardening elements, has a carbon content of 0·42–0·48%.[1–4] The hardenability of D6ac steel is better than that of AISI 4340 steel, and it can be heat-treated to achieve strengths ranging from 1241 MPa to 1792 MPa. D6ac steel is primarily designed for the ultra-high-strength structural applications.[5] It is typically used in aerospace components such as landing gears and rotating shafts and in applications that require an appropriate combination of fatigue strength and fracture toughness. D6ac steel may be welded by gas tungsten arc welding (GTAW) or by gas metal arc welding (GMAW) to produce thin sections and heavy sections, respectively, by using a filler metal of the same alloy. The electron beam welding (EBW) process is a well-established technique for fusion welding of aeronautical components. This fusion welding process uses a concentrated beam composed primarily of high-velocity electrons, which impinge on the workpiece surface.[6] The heat produced by the beam thereby allows coalescence of workpieces. In contrast to the GTAW and GMAW processes, the EBW process has a high-energy density and low heat input, resulting in a high weld depth-to-width ratio, narrow heat-affected zone (HAZ), less thermal distortion and low residual stress.[7–11]

Heat treatment of steels is an important operation in the final fabrication process of many engineering structures. Post-weld heat treatment (PWHT) is defined as any heat treatment after welding. It is often used to improve the mechanical properties or to relieve residual stress of welded steel structures. A critical function of the PWHT is the prevention of brittle fracture of the weldment. The PWHT can improve the performance of the weldment by altering its microstructures. The study by Huo *et al.*[12] on the effect of the PWHT on the mechanical properties of the EB-welded 30CrMnSiNi2A steel, the PWHT could improve the fracture toughness of the weldment. Carvalho and Lima[13] found that the laser beam (LB)-welded 300M ultrahigh-strength steel (UHSS) had poor mechanical properties, which could be improved by the tempering. Chang *et al.*[14] described the fracture characteristics of the D6ac steel tempered at 600°C and showed that its microstructure contains discrete coarse carbides at prior austenite grain boundaries. A suitable choice of PWHT is necessary to enhance the mechanical properties of fusion-welded UHSS. The literature offers limited data on the PWHT of the EB-welded UHSS, particularly of specialised D6ac steel. Thorough knowledge of this subject is necessary for understanding the combined effects of EBW and PWHT on the cold-worked D6ac steel. The present study investigates the influence of PWHT on the mechanical properties of the FF-formed D6ac EB weldment. The hardness profile of the weldments at different PWHT temperatures is also discussed. Finally, an optimum

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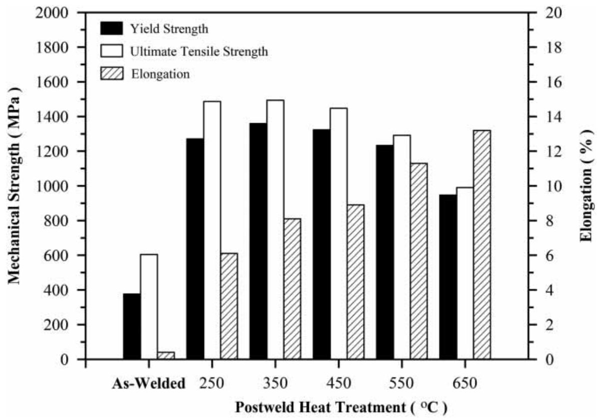
PWHT temperature for the FF-formed D6ac EB weldment is identified.

Experimental details

D6ac steel was fabricated by using the consumable-electrode vacuum arc remelting technique. D6ac steel with the chemical composition (in wt-%) of 0·47% C, 0·81% Mn, 0·28% Si, 0·01% P, 0·01% S, 0·54% Ni, 0·99% Cr, 1·06% Mo, 0·10% V and balance Fe was used in this study. A flow forming is an advanced process for fabricating thin-walled, seamless steel tubes.[15] Prior to forming, the D6ac steel was normalised by 910°C/105 min/air cooling and then machined to a wall thickness of 6·0 mm. Subsequently, the steel tube was further reduced to a wall thickness of 2·1 mm (a reduction of 65%) by forward flow forming (FFF) process. The FFF operation of the D6ac steel tube was performed in a three-roller spinning machine with a spindle speed of 60 rev min^{-1} and a feed rate of 0·7 mm rev^{-1} (the three rollers were placed at 120° angles). The resulting heavily cold-worked structures could be softened by solution treatment. In this study, the FF-formed D6ac steel tube received a solution treatment of 900°C/30 min/air cooling.

Thereafter, the FF-formed and solution-treated D6ac steel tube was EB-welded in a vacuum chamber at a pressure of $1·33 \times 10^{-2}$ Pa. The EBW process was done in one pass at a speed of 35 mm s^{-1} without preheating. The beam current and accelerating voltage were maintained at 200 and 120 kV, respectively. The distance between the gun and the workpiece was maintained at 444·5 mm. PWHT consists in heating the weldment at a controlled temperature, soaking at this temperature for a sufficiently long time and then cooling at controlled rates. If PWHT is conducted at an appropriate heating temperature and soaking time, then the weldment acquires the desired mechanical properties. In this study, the FF-formed D6ac EB weldments were heat-treated and held at the prescribed temperature (250, 350, 450, 550 or 650°C) for 2 h and then air cooled.

The tensile test was used to determine the mechanical properties (yield strength (YS), ultimate tensile strength (UTS) and elongation) of the weldments. The tensile specimens were obtained along the length of the welded steel tube and were milled to finish dimensions in accordance with the specification ASTM E370. The specimens had dimensions of 20 mm width, 160 mm length, 1·7 mm thickness and 50·8 mm gauge length. The tensile test involved two strain rates: 0·2 (mm/mm) min^{-1} was used prior to the yield point and 2 (mm/mm) min^{-1} was used after the yield point. The fracture surface of the specimens was observed with a scanning electron microscopy (SEM). The joints were sectioned perpendicular to the welding direction for metallographic analyses. Metallographic samples were then prepared using standard procedures, including mounting and grinding, as well as polishing to a 0·05 μm finish, followed by etching. The etching was carried out in a solution consisting of 3 mL of HNO_3 and 97 mL of alcohol. The Vickers hardness test was used to evaluate the local characteristics of the as-welded steel and different PWHT weldments. The hardness profile across the weld metal (WM), HAZ and base metal (BM) was measured under a test load of 2·94 N and hold time of 15 s. The Vickers hardness value was then converted to Rockwell C hardness value.

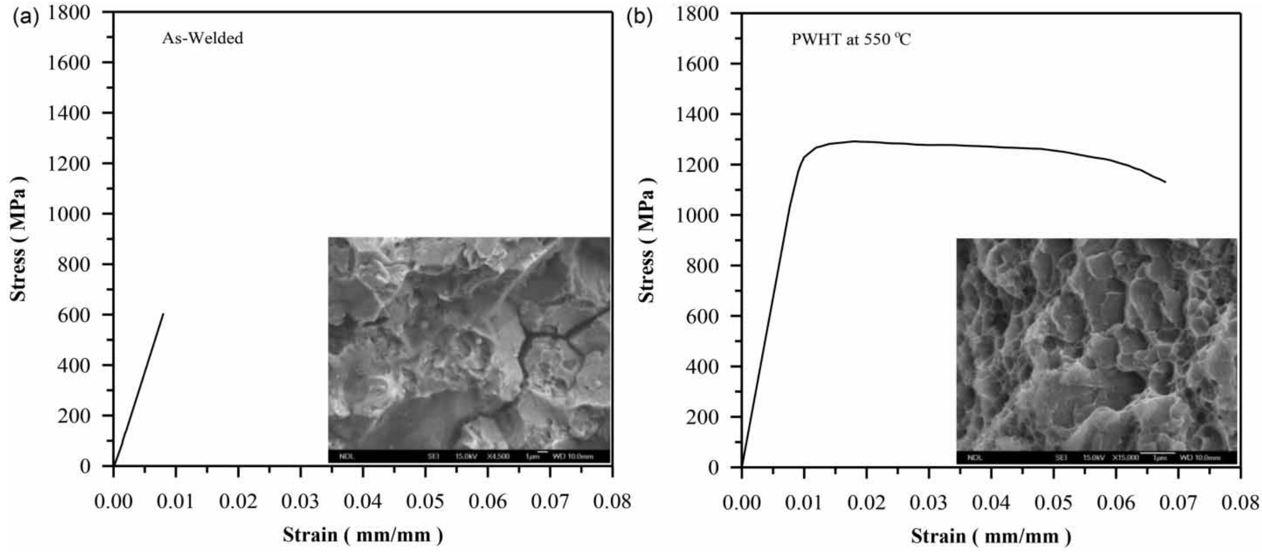


1 Mechanical properties of FF-formed D6ac EB weldments subjected to different PWHT temperatures

Results and discussion

Figure 1 shows the mechanical properties of the FF-formed D6ac EB weldments subjected to different PWHT temperatures. For each welding condition, four tensile specimens were tested and the average value was taken. Figure 2 shows the stress–strain curve and SEM fractograph for the as-welded D6ac steel and the weldment at PWHT temperature of 550°C. Fractures in the as-welded D6ac steel were located in the WM, and random solidification occurred in the fracture zone; fractures of all PWHT weldments were located in the HAZ and ductile dimples formed in the fracture zone. YS and UTS of the as-welded D6ac steel were 376·1 and 604·3 MPa, respectively, and elongation was 0·4%. Note that the as-welded D6ac steel had a low elongation because of its high dislocation density[3] and that there was almost no plastic deformation zone (Fig. 2*a*). The original D6ac steel had few misfit dislocations; when the steel underwent FFF process, its dislocation density increased because of the formation of new dislocations and because of multiplication of dislocations.[16] It can be seen that mechanical properties of the as-welded D6ac steel did not meet the requirements of the specification. As a result, the as-welded D6ac steel required further PWHT to improve the weldment performance and to meet the specified mechanical strength and elongation.

After PWHT, the FF-formed D6ac EB weldments exhibited higher YS, UTS and elongation than those of the as-welded steel. This is because PWHT decreases the dislocation density of the as-welded D6c steel, and the resulting weldment has a large plastic deformation zone (Fig. 2*b*). The largest YS and UTS (approximately 1359·2 and 1494·3 MPa, respectively) were reached when the FF-formed D6ac EB weldment was heat-treated at 350°C. The martensite start transformation temperature (Ms) of D6ac steel is approximately 320°C regardless of the cooling rate.[17] As the PWHT temperature increased to >320°C, the lower bainite formed.[18] Sajjadi reported that lower bainite exhibited mechanical properties superior to those of fully martensite.[19] Compared with those of the weldment at a PWHT temperature of 350°C, YS and UTS of the FF-formed D6ac EB weldments heat-treated at 450 and 550°C were lower, and the elongation was larger because of the formation of upper bainite. It is noteworthy that the YS of the FF-formed D6ac EB weldments heat-treated at 350



2 Stress–strain curve and SEM fractography of as-welded and weldment PWHT at 550°C

and 450°C exceeded the 1310 MPa requirement stipulated by the specification SAE AMS 6431 M. Furthermore, YS and UTS of the FF-formed D6ac EB weldment subjected to PWHT at a temperature of 650°C were 947·1 and 990·5 MPa, respectively, and its elongation was 13·2%. The FF-formed D6ac EB weldment heat-treated at 650°C had the lowest mechanical strength and the largest elongation among all specimens tested.

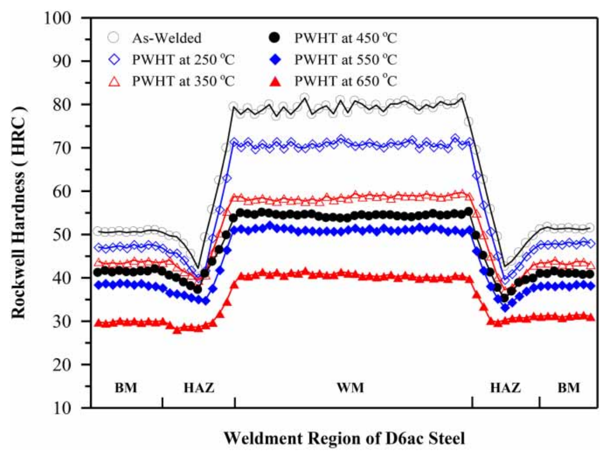
Bannister *et al.*[20] pointed out that the steel specifications for the YS/UTS ratio are specifically defined limits; the current design code limits for the YS/UTS ratio vary from 0·70 to 0·90. There is agreement that a YS/UTS ratio of up to 0·85 is satisfactory for conventional structural applications.[16] For weldments at PWHT temperatures of 350 and 450°C, the YS/UTS ratio is approximately 0·91. The results of the present study suggest that the FF-formed D6ac EB weldment heat-treated at 350–450°C and held at this temperature range for 2 h exhibits good mechanical strength and sufficient elongation, besides a high YS/UTS ratio.

Figure 3 shows the hardness profiles of the FF-formed D6ac EB weldments subjected to different PWHT temperatures. The hardness profiles indicate that the weakest region in the weldment was the HAZ. Hardness values of the WM, HAZ and BM for the as-welded D6ac steel are 80 HRC, 43 HRC and 51 HRC, respectively. The results show that the WM exhibits high hardness because of its relatively high dislocation density.[3] After PWHT, the FF-formed D6ac EB weldments exhibited hardness lower than that of the as-welded steel. In contrast to the weldment without PWHT, the FF-formed D6ac EB weldment at PWHT temperature of 250°C did not show a significant decrease in hardness (hardness values of WM, HAZ and BM are 71 HRC, 40 HRC and 47 HRC, respectively). Increasing the PWHT temperature from 350°C to 550°C decreased the hardness value of WM from 58 HRC to 51 HRC; the hardness value of HAZ decreased from 40 HRC to 35 HRC. In this study, the wall thickness of the original D6ac steel tube decreased by 65%, and the heavily cold working process of the steel tube resulted in the formation of deformation-induced martensite. The PWHT at temperatures of 350–550°C caused fully martensite to transform into a soft structure (bainite or tempered martensite), resulting in a slight decrease in the hardness value of BM (from 43 HRC to 38 HRC).

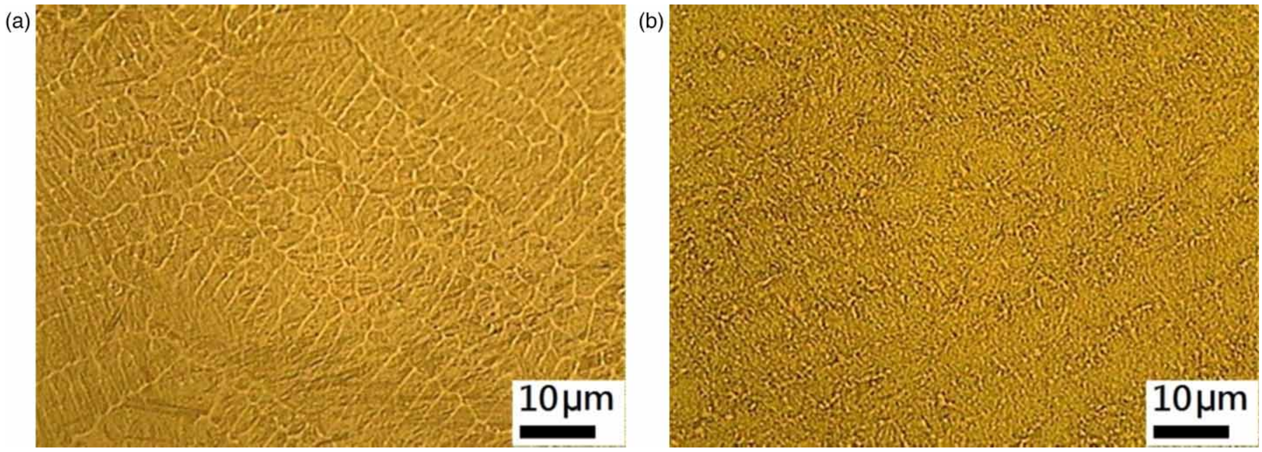
Hardness values of MW, HAZ and BM for the FF-formed D6ac EB weldment heat-treated at 650°C are 40 HRC, 29 HRC and 30 HRC, respectively. The results show that the hardness of the overtempered weldment significantly decreased. Figure 4 shows the weld microstructures of the as-welded D6ac steel and the weldment at PWHT temperature of 650°C. The weld microstructure of the as-welded D6ac steel showed long dendritic branches (Fig. 4*a*) because of rapid solidification in the molten metal after EBW. The weld microstructure of the FF-formed D6ac EB weldment subjected to PWHT at a temperature of 650°C showed the coarser carbides dispersed at the austenite grain boundaries (Fig. 4*b*). As a result, the hardness of the overtempered weldment was lower than that of the original D6ac steel.

Conclusions

The present study investigated the influence of different post-weld heat treatment temperatures on the mechanical



3 Hardness profiles of FF-formed D6ac EB weldments subjected to different PWHT temperatures



4 Weld microstructures of as-welded and weldment PWHT at 650°C

properties and hardness profile of forward flow-formed D6ac electron beam weldments. The weldments were heat-treated and held at the prescribed temperature (250, 350, 450, 550 or 650°C) for 2 h, and then air cooled. An optimum post-weld heat treatment temperature for the forward flow-formed D6ac electron beam weldment has been identified. The main conclusions obtained from this study are as follows:

(1) The as-welded D6ac steel exhibits very poor mechanical strength and elongation. After post-weld heat treatment, a large improvement in the mechanical properties of the D6ac electron beam weldment is achieved.

(2) The D6ac electron beam weldments heat-treated at 350°C reach the largest yield strength and ultimate tensile strength (approximately 1359·2 and 1494·3 MPa, respectively). The largest elongation (approximately 13·2%) is reached when the weldment is heat-treated at 650°C.

(3) The D6ac electron beam weldment subjected to a post-weld heat treatment temperature of 650°C exhibits an overtempered state. The hardness of the overtempered weldment is lower than that of the original D6ac steel.

(4) The forward flow-formed D6ac electron beam weldment heat-treated at 350–450°C and held at this temperature range for 2 h exhibits high mechanical strength and sufficient elongation and a yield strength/ultimate tensile strength ratio of 0·91.

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References

1. L. W. Tsay, C. S. Chung and C. Chen: 'Fatigue crack propagation of D6AC laser welds', *Int. J. Fatigue*, 1997, **19**, 25–31.
2. S. C. Wu, H. C. Wen, K. H. Tseng, W. H. Yau, M. J. Wu, C. P. Chou and W. K. Hsu: 'Sliding wear resistance of tempered D6ac steel', *Vac.*, 2013, **87**, 89–94.
3. S. C. Wu, K. H. Tseng, H. C. Wen, M. J. Wu and C. P. Chou: 'Tribological behavior of electron beam D6ac weldment', *Appl. Surf. Sci.*, 2013, **264**, 45–51.
4. D. Lian: 'Microstructure properties of tempered D6ac steel', *Appl. Surf. Sci.*, 2013, **264**, 100–104.
5. G. L. Peterman and R. L. Jones: 'Effects of quenching variables on fracture toughness of D6AC steel aerospace structures', *Met. Eng. Quart.*, 1975, **15**, 59–64.
6. L. Jeffus: 'Welding: principles and applications', 7th edn, 889; 2011, New York, Delmar Cengage Learning.
7. C. C. Huang, Y. C. Pan and T. H. Chuang: 'Effects of post-weld heat treatments on the residual stress and mechanical properties of electron beam welded SAE 4130 steel plates', *J. Mater. Eng. Perform.*, 1997, **6**, 61–68.
8. R. Lindau, M. Klimenkov, U. Jäntsch, A. Möslang and L. Commin: 'Mechanical and microstructural characterization of electron beam welded reduced activation oxide dispersion strengthened–Eurofer steel', *J. Nucl. Mater.*, 2011, **416**, 22–29.
9. A. Çalik, M. S. Karakaş and R. Varol: 'Fatigue behavior of electron beam welded dissimilar metal joints', *Weld. J.*, 2012, **91**, 50–52.
10. G. D. Janaki Ram, A. Venugopal Reddy, K. Prasad Rao and G. Madhusudhan Reddy: 'Microstructure and mechanical properties of Inconel 718 electron beam welds', *Mater. Sci. Technol.*, 2013, **21**, 1132–1138.
11. C. J. Tsai and L. M. Wang: 'Improved mechanical properties of Ti-6Al-4V alloy by electron beam welding process plus annealing treatments and its microstructural evolution', *Mater. Des.*, 2014, **60**, 587–598.
12. L. X. Huo, F. R. Chen, Y. F. Zhang, L. Zhang, F. J. Liu and G. Chen: 'Effect of post-weld heat treatment on microstructure and fracture toughness of 30CrMnSiNi2A steel welded joints', *J. Mater. Sci. Technol.*, 2003, **19**, 483–486.
13. S. M. de Carvalho and M. S. F. de Lima: 'Laser beam welding tempered 300M ultrahigh mechanical strength steel', *J. Braz. Soc. Mech. Sci. Eng.*, 2012, **34**, 18–23.
14. T. L. Chang, L. W. Tsay and C. Chen: 'Influence of gaseous hydrogen on the notched tensile strength of D6ac steel', *Mater. Sci. Eng. A*, 2001, **316**, 153–160.
15. Y. J. Lee, I. K. Lee, S. C. Wu, M. C. Kung and C. P. Chou: 'Effect of post-weld heat treatments on microstructure and mechanical properties of electron beam welded flow formed maraging steel weldment', *Sci. Technol. Weld. Join.*, 2007, **12**, 266–273.
16. S. C. Wu, H. C. Wen, M. J. Wu and C. P. Chou: 'Fracture responses of microstructures of electron beam-welded D6AC', *Vac.*, 2012, **86**, 1828–1833.
17. Y. W. Lee, Y. I. Son and S. J. Lee: 'Microstructure and mechanical properties of spheroidized D6AC steel', *Mater. Sci. Eng. A*, 2013, **585**, 94–99.
18. Kh. Abbaszadeh, H. Saghafian and Sh. Kheirandish: 'Effect of bainite morphology on mechanical properties of the mixed bainite-martensite microstructure in D6AC steel', *J. Mater. Sci. Technol.*, 2012, **28**, 336–342.
19. S. A. Sajjadi and S. M. Zebarjad: 'Isothermal transformation of austenite to bainite in high carbon steel', *J. Mater. Process. Technol.*, 2007, **189**, 107–113.
20. A. C. Bannister, J. Ruiz Ocejo and F. Gutierrez-Solana: 'Implications of the yield stress/tensile stress ratio to the SINTAP failure assessment diagrams for homogeneous materials', *Eng. Fract. Mech.*, 2000, **67**, 547–562.