Effect of Multiple Thermal Cycles on the Microstructure and Mechanical Properties of AISI 1045 Weldments

Muhammad Atif Makhdoom,* Furqan Ahmed, Ifitkhar Ahmed Channa, Aqil Inam, Fahad Riaz, Sajid Hussain Siyal, Muhammad Ali Shar, and Abdulaziz Alhazaa

ABSTRACT: AISI 1045 medium carbon steel sheets having 10 mm thickness were subjected to the shielded metal arc welding process with three, five, and seven passes. The variations in the microstructure due to multiple thermal cycles in the heat-affected zone (HAZ), base metal (BM), and fusion zone (FZ) have been investigated and correlated with measured mechanical properties. Upon comparing fracture mechanics and mechanical properties with microstructural observations, it is elucidated that samples become ductile by increasing the number of thermal cycles which can be attributed to the transformations in the ferrite morphology in the HAZ. Based on mechanical, microstructural, and fracture analysis, it is concluded that post-weld heat treatment can be avoided if the number of passes during welding is increased.

1. INTRODUCTION

The induction of heat during multipass welding incorporates a heat-treatment effect in the microstructure which is analogues if the same sample is treated otherwise in a furnace under similar conditions. The high heating and cooling cycles, however, drastically change the microstructure in the fusion zone (FZ) and heat-affected zone (HAZ) during welding which is normally not observed after usual heat treatment processes in the same steel. High peak temperature during welding is the main reason for change which becomes more pronounced during multipass welding. In multi-pass welding, different zones are formed in the weldment based on microstructural changes which occur with temperature variation.

Medium carbon steels have found a wide range of engineering applications due to their better mechanical properties and good response toward heat treatment, for example, in shafts, pressure structures, bogie frames of railway vehicles, and so forth. In case of higher-carbon range medium carbon steels, the HAZ attains full hardness without any alloying addition which is more likely due to the formation of martensite. This endows weldments with low ductility and high susceptibility to hydrogen induction and cold cracking. The tendency of martensite formation in the HAZ during welding deteriorates the mechanical properties of medium carbon steel when compared to those of low carbon steel. However, martensite in the HAZ of the first weld pass is tempered by the heat ensuing from the deposition of subsequent passes. These microstructural changes arising during welding not only affect its electrochemical properties but also affect mechanical properties. These changes are difficult to simulate using computer-aided software which is otherwise very helpful in many engineering applications. This is due to lack of understanding of the phase transformations occurring within the material as a result of transient thermomechanical—chemical boundary conditions. This demands an in-depth knowledge of microstructural changes along with other parameters during welding. Therefore, the effect of the microstructure on the mechanical properties during welding has been the area of interest in contemporary research, but the literature on medium carbon steel is scanty in this particular direction and hence the present research. In this article, the effect of multi-pass welding on the microstructural variations in different welding zones of medium carbon steel has been investigated by eliminating the need for post-weld heat treatment (PWHT) which can save time and cost. The obtained results have been correlated with the mechanical properties and fracture mechanism.
2. EXPERIMENTATION

Rolled plates of medium carbon steel AISI 1045 having 10 mm thickness were used as the base metal (BM). Bevel angles of 40, 60, and 80° were made for three, five, and seven passes, respectively. Butt weld joints with the designated filler metal (8018-B2) were made using the shielded metal arc welding (SMAW) process as per AWS codes and standards. To ensure heat input in each pass, marks were made along the length of the plate as shown schematically in Figure 1.

In this specially adapted technique, every marked segment was welded with a single electrode at constant speed which then lifted off as the next mark was reached. This technique helped avoid weld discontinuity which may otherwise be found in test specimens leading to ambiguous results. Chemical compositions and welding parameters are given in Tables 1−3.

For optical microscopy, three samples were precisely sectioned from the BM, FZ, and HAZ of all three types of welded joints and subjected to the conventional metallographic sample preparation technique followed by etching in 3% Nital for 10 s.

To investigate the morphology of fracture, a fractographic study was carried out which has become a popular technique with the invention of scanning electron microscopy (SEM). Field-emission SEM (FESEM) is also reported in the literature for the said analysis. In this work, FEI Inspect S50 SEM was used to examine the fractured surface of tensile-tested samples and take micrographs at different magnifications. The river pattern, dimples, lamellar tearing, and so forth, which help conclude the breaking pattern. The fractography study of tensile- and impact-tested samples is already documented.

Nine samples for each test, that is, tensile, bend, and V-notch Charpy impact, were marked as per ASTM-E8 and sectioned from all three welded plates to ensure the consistency in results. A wire-cut electric discharge machine (EDM) was used to avoid any further changes in the microstructure which may otherwise occur due to heat generation in traditional cutting processes.

Bend (as per ASTM A36) and tensile tests were performed using Shimadzu UTM, model: UMH-200A T.V. having 200 ton capacity, while the impact test was performed on a Laryee Technology machine, model: CMT 2230.

### Table 1. Nominal Chemical Composition (wt %, Balance Fe) of the Base Metal

| C   | Si  | Mn  | Cr  | Ni  | Mo  | W   | Nb  | S   | P    |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 0.43| 0.22| 0.64| 0.13| 0.068| 0.023| 0.013| 0.014| 0.022| 0.097 |

### Table 2. Nominal Chemical Composition (wt %, Balance Fe) and Mechanical Properties of the Filler Metal (8018-B2)

| C    | Si  | Mn  | Cr  | Ni  | Mo  | W   | S   | P | UTS,  |
|------|-----|-----|-----|-----|-----|-----|-----|---|------|
| 0.071| 0.41| 0.81| 1.12| 0.51| <0.005| <0.010| 630 |   |      |

3. RESULTS AND DISCUSSION

Figure 2 shows results of tensile strengths, yield strengths, and percentage elongation for all three passes. Results show that both ultimate tensile strength (UTS) and yield strength (YS) possess an increasing trend with the number of passes. The UTS of un-welded AISI 1045 steel is 742 Mpa, whereas for the samples subjected to three passes, the UTS was slightly reduced by 0.67%. However, for the samples subjected to five and seven passes, the UTS was increased by 2.42 and 7.14%, respectively. The percentage of elongation was also increased with the number of passes. All the samples were fractured from the HAZ. However, the side view of the fractured samples depicts that by increasing the number of passes, the fracture plane changes its direction from perpendicular to an angle of approximately 45°. This is a typical behavior of brittle to ductile transition—see Figure 3a(i−iii). For reference, the same sample is placed at the top in the horizontal position to differentiate FZ and HAZ areas. Here, it is pertinent to note that the said picture of the reference sample is of before removal of the weld reinforcement (capping pass) prior to testing.

The bend test results under three-point load conditions show that samples with three and five passes failed to qualify the test—see Figure 3b(i,ii). High-magnification images show that fracture occurred at the HAZ. However, the samples subjected to seven passes qualified the test, and there was no fracture evident in the samples—see Figure 3b(iii). Figure 4 shows the results of Charpy V-notch absorbed energy versus number of passes. The graph exhibits an increase in the absorbed energy with the number of passes. The toughness of the bare AISI 1045 steel is 150 joules, but the toughness of the samples subjected to three passes was slightly decreased by 5.33%. However, toughness of the samples subjected to five and seven passes was tremendously increased by 70 and 96.67%, respectively. It has been reported that toughness of the FZ is lower than that of the BM and HAZ, but it is opposite in our case. This can be attributed to the number of thermal cycles that increase linearly with the number of passes which eventually modifies the previously formed microstructure. This phenomenon was investigated by analyzing the microstructures as explained in detail in the following sections.

The microstructure of the BM—see Figure 5a—shows a combination of the pearlitic (black) and allotriomorphic ferrite (αa) (white) microstructure with a ratio of approximately 60:40 when observed at higher magnification—see Figure 5b.

Microstructures of the FZ of all the passes have a typical columnar morphology—see Figure 5c—but the grain size is enlarged as the number of passes increases from three to seven.
Table 3. Welding Data for Three, Five, and Seven Passes

| number of pass | length of pass (mm) | inter-pass temperature (°C) | voltage (V) | current (Amp) | average travel speed between each mark (mm/min) | diameter of electrode (mm) | POL |
|----------------|---------------------|-------------------------------|-------------|---------------|-----------------------------------------------|------------------------|-----|
| Welding Data for Three Passes | | | | | | | |
| 1 | 304 | 33 | 23 | 84 | 44 | 2.5 | DCEP |
| 2 | 304 | 46 | 25 | 95 | 65 | 2.5 | DCEP |
| 3 | 304 | 77 | 24 | 88 | 72 | 4.0 | DCEP |
| Welding Data for Five Passes | | | | | | | |
| 1 | 304 | 42 | 23 | 79 | 64 | 2.5 | DCEP |
| 2 | 304 | 68 | 25 | 103 | 64 | 2.5 | DCEP |
| 3 | 304 | 75 | 24 | 75 | 95 | 2.5 | DCEP |
| 4 | 304 | 59 | 24 | 83 | 74 | 2.5 | DCEP |
| 5 | 304 | 76 | 26 | 111 | 67 | 4.0 | DCEP |
| Welding Data for Seven Passes | | | | | | | |
| 1 | 304 | 33 | 22 | 84 | 75 | 2.5 | DCEP |
| 2 | 304 | 48 | 23 | 95 | 86 | 2.5 | DCEP |
| 3 | 304 | 49 | 23 | 95 | 83 | 2.5 | DCEP |
| 4 | 304 | 48 | 24 | 95 | 75 | 2.5 | DCEP |
| 5 | 304 | 48 | 24 | 95 | 86 | 2.5 | DCEP |
| 6 | 304 | 49 | 25 | 95 | 87 | 2.5 | DCEP |
| 7 | 304 | 79 | 25 | 88 | 89 | 4.0 | DCEP |

Figure 2. Average comparative values of tensile strength, yield strength, and percentage elongation for the BM and three, five, and seven passes.

Figure 3. Side views of (a) tensile-tested samples showing fracture surface morphologies and (b) bend-tested samples with higher magnifications (right) showing crack formation after (i) three, (ii) five, and (iii) seven passes.
At higher magnifications—see Figure 5d–f—the FZ shows the presence of ferrite at grain boundaries as allotriomorphic ferrite, Widmanstätten ferrite (atw), and acicular ferrite (atac). Widmanstätten ferrite is more pronounced in the FZ of three passes and with a less tendency in the FZ of five passes. In the FZ of seven passes, Widmanstätten ferrite is completely eliminated with the formation of acicular ferrite—see Figure 5f—which is comparatively lesser in the FZ of five passes and completely absent in the FZ of three passes.

Analysis of HAZ microstructures—see Figure 5g–i—clearly reveals a linear increase in the number of fine grains as the number of passes increases from three to seven. Coarse-grained pearlite in the three-pass HAZ—see Figure 5g—is encapsulated by allotriomorphic ferrite as grain boundary ferrite along with Widmanstätten ferrite which is typically nucleated at alpha–gamma grain boundaries and extended into untransformed austenite grain interiors.27 The amount of Widmanstätten ferrite is reduced or becomes almost negligible when the number of passes is increased from three to five with the refinement of coarse-grained pearlite—see Figure 5h. This can be attributed to multiple thermal cycles which are higher in case of five passes. This fact is further amplified as the number of passes is increased from five to seven, producing fine-grained pearlite with a high volume fraction of equiaxed polygonal ferrite—see Figure 5i.

The microstructure of the BM—see Figure 5a,b—is comparatively composed of a less amount of ferrite when compared with that of the HAZ and FZ. During welding, the temperature of the BM at a distance from the FZ remains below 200 °C, and hence, no microstructural variations occur.4

The number of thermal cycles with subsequent passes increases the austenite grain size which, in turn, reduces the grain boundary areas which are actually the preferential sites for the nucleation of proeutectoid ferrite, and therefore, coarsening of ferrite grain size occurs in the FZ with the number of passes increasing from three to seven. Moreover, less nucleation sites were available for pearlite nucleation due to limited availability of the ferrite–austenite interface which resulted in reduction of the pearlite volume fraction with the number of passes. The percent dilution of BM composition with the 8018-B2 filler metal also resulted in the formation of a large volume fraction of ferrite with different morphologies in the FZ. The nucleation of acicular ferrite occurs mostly at non-metallic inclusions.28,29 The addition of “Mo” from the filler metal also tended to preclude pro-eutectoid ferrite and favored acicular ferrite. The significant density of these nucleation sites in the FZ resulted in the formation of such a microstructure instead of banite30,31 and hence promoted strength and toughness of the material.32 However, the presence of allotriomorphic ferrite as grain boundary ferrite is unfavorable for the toughness,31 and a brittle fracture mode is more likely which is proportional to the amount of Widmanstätten ferrite that forms within the microstructure of the weldment along with allotriomorphic ferrite.32,34 Therefore, upon considering the combined effect of pearlite grain size, relative volume fractions of ferrite–pearlite phases, and the presence of a large amount of Widmanstätten ferrite in the three-pass HAZ—see Figure 5g—and FZ—see Figure 5d, a brittle fracture is registered.

As the number of passes was increased, the transition from the brittle to the ductile fracture mode was observed with improved mechanical properties. The following reasons can be attributed to these observations: (i) the transformation of Widmanstätten ferrite to other forms of ferrite with subsequent thermal cycles in five and seven passes, see Figure 5g,h, and (ii) reduction in the grain size of the pearlite with the formation of a large amount of polygonal ferrite.

Mechanical tests showed that the strength of the weldments improved with the number of passes, but the region of the HAZ proved to be the weakest part as the weldments failed from here. The area of the HAZ is reheated during multipass welding which results in the development of different phases. It is reported that formation of banite in the HAZ in low carbon steel results in a brittle fracture,35 but here, in case of medium carbon steel, such a structure is not evident in subsequent passes.

Figure 6 shows the fractographs taken with SEM from fractured surfaces after tensile tests. Figure 6a clearly shows that a typical cleavage-type transgranular brittle fracture which is evident from broken grains or cleavage facets and cracks—see white arrows in Figure 6a—is present on the fracture surface. The presence of Widmanstätten ferrite in the three-pass weldment provides suitable sites to initiate the transgranular cracks, which are further augmented by the presence of large grains of pearlite. This has reduced overall toughness of the sample. Ductile fracture was found in the samples subjected to seven passes which is evident from the typical fibrous surface consisting of a considerable number of dimples/micro-voids—see white arrows in Figure 6c. Smaller size of dimples is associated with grain refinement. Elongated and coalesced dimples are the indicator of high plasticity and elongation as evident from the results of mechanical tests. Figure 6b, however, shows mixed fracture where cleavage fracture—see white arrows (ii) in Figure 6b—and shear dimples—see white arrows (i) in Figure 6b—both can be seen.

4. CONCLUSIONS

The SMAW process was carried out on medium carbon steel with three, five, and seven passes followed by mechanical characterization without PWHT. Following inferences are made from the current investigations:

- Reduction in grain size with the increasing number of passes is evident in the HAZ, resulting in the improvement in UTS and toughness of the weldment by approximately 7.14 and 96.67%, respectively.
- Multipass welding option can be adopted without PWHT in medium carbon steels wherever high toughness is required without compromising UTS.
Figure 5. Microstructures of (a) BM at lower magnification, (b) BM at higher magnification, (c) FZ at lower magnification, (d) FZ at higher magnification of three passes, (e) FZ at higher magnification of five passes, (f) FZ at higher magnification of seven passes, (g) HAZ of three passes, (h) HAZ of five passes, and (i) HAZ of seven passes.
• Formation of a high-volume fraction of polygonal ferrite and the absence of Widmanstätten ferrite in the seven-pass weldment demonstrated ductile fracture which was otherwise brittle in the three-pass weldment, where a comparatively higher volume fraction of Widmanstätten ferrite and large grain size were present.

• Fractographic study of the samples showed a systematic variation in the microstructure resulting in transition from transgranular brittle to ductile fracture with a mixed fracture in the five-pass weldment. These observations are also evident from tensile, bend, and toughness results and hence justify the fracture analysis.

■ AUTHOR INFORMATION

Corresponding Author

Muhammad Atif Makhdoom — Institute of Metallurgy and Materials Engineering, University of the Punjab, Lahore 54590, Pakistan; orcid.org/0000-0001-7408-0689; Email: atif.imme@pu.edu.pk

Authors

Furqan Ahmed — Metallurgical & Materials Engineering Department, Faculty of Chemical, Metallurgical and Polymer Engineering, University of Engineering & Technology (UET), Lahore 54000, Pakistan
Iftikhar Ahmed Channa — Department of Metallurgical Engineering, NED University of Engineering and Technology, Karachi 75270, Pakistan
Aqil Inam — Institute of Metallurgy and Materials Engineering, University of the Punjab, Lahore 54590, Pakistan
Fahad Riaz — Institute of Metallurgy and Materials Engineering, University of the Punjab, Lahore 54590, Pakistan
Sajid Hussain Siyal — Department of Metallurgy and Materials Engineering, Dawood University of Engineering and Technology, Karachi 74800, Pakistan; orcid.org/0000-0002-9041-0649
Muhammad Ali Shar — Department of Mechanical & Energy Systems Engineering, Faculty of Engineering and Informatics, University of Bradford, Bradford BD7 1DP, U.K.
Abdulaziz Alhazaa — Department of Physics and Astronomy, College of Science, King Saud University, Riyadh 11451, Saudi Arabia

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c05249

Author Contributions

The manuscript was written through contributions of all authors.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors would like to acknowledge the Researcher’s Supporting Project Number (RSP-2021/269) King Saud University, Riyadh, Saudi Arabia, for their support in this work.

■ REFERENCES

(1) Zhang, J. J.; Zhao, L.; Rosenkranz, A.; Song, C. W.; Yan, Y. D.; Sun, T. Nanosecond Pulsed Laser Ablation on Stainless Steel — Combining Finite Element Modeling and Experimental Work. Adv. Eng. Mater. 2019, 21, 1900193.
(2) Zhang, J.; Zhao, L.; Rosenkranz, A.; Song, C.; Yan, Y.; Sun, T. Nanosecond pulsed laser ablation of silicon-finite element simulation and experimental validation. J. Micromech. Microeng. 2019, 29, 075009.
(3) Gachot, C.; Grützmacher, P.; Rosenkranz, A. Laser Surface Texturing of TiAl Multilayer Films—Effects of Microstructure and Topography on Friction and Wear. Lubricants 2018, 6, 36.
(4) Kou, S. Welding Metallurgy, 2nd ed.; Wiley: New York, 2003.
(5) Eisenhuttenleute, V. D. Steel—A Handbook for Materials Research and Engineering: Volume 1: Fundamentals; Springer Berlin Heidelberg, 1991.

(6) Albutt, K.; Garber, S. Effect of heating rate on the elevation of the critical temperatures of low-carbon mild steel. J. Iron Steel Inst. 1966, 204, 1217–1222.

(7) Goo, B.-C. Effect of Post-Weld Heat Treatment on the Fatigue Behavior of Medium-Strength Carbon Steel Weldments. Metals 2021, 11, 1700.

(8) Sugimoto, K.-i.; Hojo, T.; Srivastava, A. K. Low and medium carbon advanced high-strength forging steels for automotive applications. Metals 2019, 9, 1263.

(9) Senthilkumar, T.; Ajiboye, T. K. Effect of heat treatment processes on the mechanical properties of medium carbon steel. J. Miner. Mater. Charact. Eng. 2012, 11, 143–152.

(10) Alawode, A. Effects of Cold Work and Stress Relief Annealing Cycle on the Mechanical Properties and Residual Stresses of Cold-Drawn Mild Steel Rod, M. Eng Thesis; University of Ilorin, 2002. Thesis

(11) Jones, D. R.; Ashby, M. F. Engineering Materials 2: An Introduction to Microstructures, Processing and Design, 2nd ed.; Butterworth-Heinemann: Elsevier Ltd.: New York, 1998.

(12) Linnert, G. E. Welding Metallurgy; American Welding Society: Miami, 1967; Vol. 2.

(13) Mahdooom, M. A.; Kamran, M.; Awan, G. H.; Mukhtar, S. Effect of multipasses on microstructure and electrochemical behavior of weldments. Metall. Mater. Trans. A 2013, 44, 5505–5512.

(14) Van der Velden, A. Engineous Software: GT 2007-27555. Proc. ASME Turbo Expo; ASME: Montreal, 2007; pp 87–93.

(15) DuPont, J. N.; Babu, S.; Liu, S. Welding of materials for energy applications. Metall. Mater. Trans. A 2013, 44, 3385–3410.

(16) Alawode, A. Effects of Cold Work and Stress Relief Annealing Cycle on the Mechanical Properties and Residual Stresses of Cold-Drawn Mild Steel Rod, M. Eng Thesis; University of Ilorin, 2002. Thesis

(17) Bodude, M. A.; Momohjimoh, I. Studies on effects of welding parameters on the mechanical properties of welded low-carbon steel. J. Miner. Mater. Charact. Eng. 2015, 03, 142.

(18) Sarkari Khorrami, M. S.; Mostafaei, M. A.; Pouraliakbar, H.; Kokabi, A. H. Study on microstructure and mechanical characteristics of low-carbon steel and ferritic stainless steel joints. Mater. Sci. Eng., A 2014, 608, 35–45.

(19) Görgen, A.; Bostan, B.; Özdemir, A. T. Heat treatment in two phase region and its effect on microstructure and mechanical strength after welding of a low carbon steel. Mater. Des. 2007, 28, 897–903.

(20) Ghosh, M.; Hussain, M.; Gupta, R. K. Effect of welding parameters on microstructure and mechanical properties of friction stir welded plain carbon steel. ISIJ Int. 2012, 52, 477–482.

(21) Masters, J. E. Fractography of Modern Engineering Materials: Composites and Metals; ASTM International, 1987; Vol. 1.

(22) Pandey, C.; Mahapatra, M. M.; Kumar, P.; Sirohi, S. Fracture behaviour of creep F91 welded sample for different post weld heat treatments condition. Eng. Fail. Anal. 2019, 95, 18–29.

(23) Dewan, M. W.; Liang, J.; Wahab, M.; Okeil, A. M. Effect of post-weld heat treatment and electrolytic plasma processing on tungsten inert gas welded AISI 4140 alloy steel. Mater. Des. 2014, 54, 6–13.

(24) Pandey, C.; Saini, N.; Mahapatra, M. M.; Kumar, P. Study of the fracture surface morphology of impact and tensile tested cast and forged (C&F) Grade 91 steel at room temperature for different heat treatment regimes. Eng. Fail. Anal. 2017, 71, 131–147.

(25) Ku, J.; Ho, N.; Tjong, S. Properties of electron beam welded SAF 2205 duplex stainless steel. J. Mater. Process. Technol. 1997, 63, 770–775.

(26) Chen, Y.; Feng, J.; Li, L.; Chang, S.; Ma, G. Microstructure and mechanical properties of a thick-section high-strength steel welded joint by novel double-sided hybrid fibre laser-arc welding. Mater. Sci. Eng., A 2013, 582, 284–293.

(27) Babu, S. S. The mechanism of acicular ferrite in weld deposits. Curr. Opin. Solid State Mater. Sci. 2004, 8, 267–278.