Dissimilarly Laser Welded High Entropy Alloy and Stainless Steel 304

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Abstract

This research explores the dissimilar welding of High Entropy Alloy (HEA), specifically FeNiMnCr18, with conventional Stainless Steel (SS 304) using laser welding, without the use of filler metal. The study employs state-of-the-art techniques, including arc melting for alloy fabrication and laser beam welding (LBW) for joint formation. Experimental parameters, such as laser power, scanning speed, and beam focus, are optimized based on a comprehensive literature review. Noteworthy findings from prior studies on dissimilar alloy welding are incorporated to enhance weld quality. The investigation delves into the influence of shielding gases, focusing on nitrogen, on porosity mitigation during laser welding. Mechanical testing, microstructure characterization through optical and scanning electron microscopy, and Radiography testing contribute to a thorough evaluation of the welded joints. The research aims to advance the understanding of dissimilar welding involving HEAs and conventional alloys, offering valuable insights for applications in critical structural scenarios. The weld joint formed was defect-free and had an average hardness of 154.6 HV.

Keywords: HEAs; Dissimilar Welding; Laser Beam Welding; Mechanical Testing; Microstructure Characterization; SS 304

1. Introduction

The contemporary landscape of structural material research is marked by an increasing exploration of dissimilar welding techniques, particularly leveraging the advantages of laser beam welding (LBW). In this context, the fusion of High Entropy Alloys (HEA) with conventional alloys stands as a pivotal area of investigation. HEAs, characterized by their unique compositional diversity and consequential material properties, present a promising avenue for various structural applications as discussed by N. K. Adomako, 2021 [1]. Laser welding, being a cutting-edge technique, is gaining prominence due to its precision, efficiency, and applicability in critical structural scenarios.

The primary focus of this research is to explore dissimilar welding of a specific HEA, 27Fe-28Ni-27Mn-18Cr in atomic percent, with Stainless Steel grade 304 (SS 304), employing LBW without the use of filler metal. The HEA was previously developed by Z. Wu, 2006 [2] and was extensively studied for nuclear irradiation by Kumar, 2016 [3]. This study delves into uncharted territories of HEA welding, especially with the latest LBW technology, to contribute insights and methodologies for potential structural applications.

The distinctions of LBW, Gas Tungsten Arc Welding, and other methods are analyzed, with a particular emphasis on their welding application to HEAs and conventional alloys. The study also encapsulates essential parameters such as hardness properties, laser parameters, and shielding gases, establishing a foundation for the subsequent experimental work.

Experimentation details are elucidated, covering alloy preparation, sample cutting, and the LBW process. The choice of laser welding parameters is rationalized based on an extensive review and prior studies, ensuring the optimization of power, speed, and focus for achieving sound weld joints. The role of shielding gases, particularly nitrogen, is highlighted, drawing from recent research demonstrating its effectiveness in mitigating porosity during laser welding by Hafez, 2022 [4].

The methodology includes a meticulous sequence of steps, from alloy preparation through vacuum arc melting to the intricate process of laser welding dissimilar materials. Handheld X-ray fluorescence (XRF) testing provides aids in confirming chemical compositions. Subsequently, radiography testing evaluates internal integrity, paving the way for hardness testing and microstructure characterization.

Mechanical testing involves micro-hardness measurements, each offering valuable data on the strength and hardness of the welded joints. Microstructure characterization utilizes optical and scanning electron microscopy (SEM) to delve into the intricate details of the weld zone.

This research reveals a comprehensive exploration of dissimilar welding with a focused lens on HEA and SS 304, demonstrating a meticulous blend of theoretical foundations, experimental techniques, and analytical methodologies. The insight gained from this research contributes to the evolving landscape of advanced welding technologies, with potential applications in critical structural scenarios.

2. Experimentation

2.1. Alloy Preparation

The synthesis of the high entropy alloy (HEA) involves the precise arc melting of pure Fe (99.95%), Ni (99.95%), Mn (99.95%), and Cr (99.95%) under a Ti-gettered argon atmosphere. Executed in a vacuum arc melting furnace with a water-cooled copper hearth, the process ensures a controlled environment with a vacuum maintained at 10^{-5} torr. The alloy buttons are subjected to five cycles of melting to guarantee homogeneity. Precise calculations determine the required element weights, which are cleaned in an ultrasonic cleaner using ethanol before being used for the melting process.

2.2. Handheld XRF

Handheld XRF was used to identify whether the composition was made as per added elements. The results suggested that the composition was like what was predicted. Furthermore, SS 304 procured locally was also tested with XRF to confirm its grade before welding.

2.3. Sample Cutting for Laser Beam Welding (LBW)

Electric Discharge Machining (EDM) wire cutting is employed to extract samples for laser beam welding (LBW). Button samples, with a diameter of approximately 24 mm and a height of 9 mm, undergo EDM wire cutting to obtain 1.5 mm thick plates for subsequent welding experiments. Additionally, Stainless Steel grade

304 plates, 1.5 mm thick and 300 mm long, undergo EDM wire cutting to produce plates with dimensions suitable for laser welding.

2.4. Laser Beam Welding (LBW)

The dissimilar welding process unfolds through laser beam welding, executed using a ytterbium-based Laser welding system. Optimized parameters; derived from the detailed work of Oliveira, 2022 [5], Zhang, 2023 [6], and Katayama, 2013 [7]; involve a power of 2.20 kW, welding speed of 780 mm/min (0.78 m/min), and nitrogen as a shielding gas at a flow rate of 15 l/min. The use of a continuous laser system ensures precise and efficient welding, generating a defect-free butt weld joint.

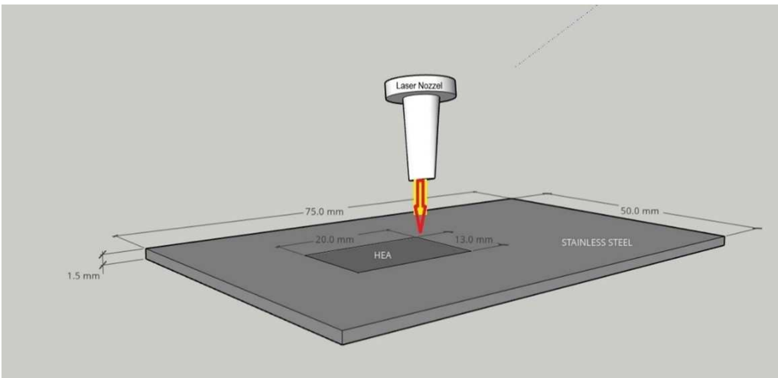

Fig. 1. Laser Beam Welding process schematic diagram along with dimensions of samples.

2.5. Grinding and Polishing

The extracted samples from the EDM wire cut had to undergo grinding and polishing to prepare them for microstructure characterization and hardness testing. Silicon carbide emery paper, ranging from P600 to P2000 grit sizes, is employed for grinding. Alumina slurry of 1µ and 0.5µ ensures a polished, scratch-free surface. Following grinding and polishing, the samples are cleaned in ethanol and deionized water to eliminate residual particles.

3. Results and Discussion

3.1. Optical Microscopy

Optical microscopy was employed to assess the top side of the welded sample after etching, revealing crucial details about grain growth orientation and welded bead thickness. The interface between the high entropy alloy (HEA) and stainless steel (SS 304) exhibited columnar grain growth near the interfaces, extending towards the center. Equiaxed grains were observed at the center, indicating prolonged cooling time. The SS 304 and weld zone interface, along with the HEA and weld zone interface, depicted distinct grain growth patterns. The bead thickness obtained after welding was roughly 2.25 mm as seen in the optical image. The top side shows the SS 304 and weld zone interface and the bottom side shows the HEA and weld zone interface. Furthermore, in Stainless Steel 304 (received in cold rolled condition) martensitic presence is seen because of cold rolling deformation done on it as seen in a similar case by Zhang, 2023 [6].

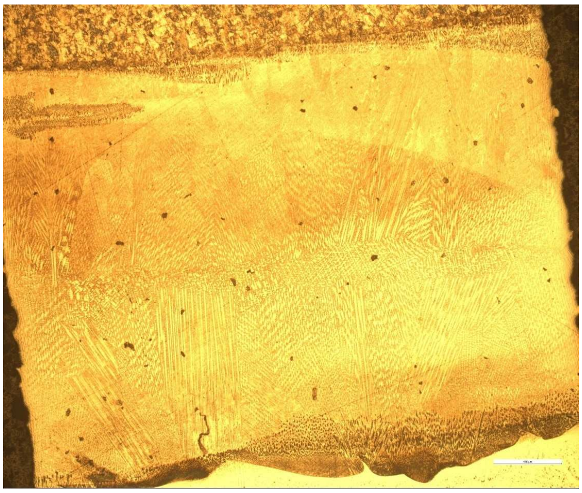

Fig. 2. Optical Microscopy image showing the welded region and base metals. HEA on the bottom and SS 304 on top.

3.2. Scanning Electron Microscopy

SEM was performed for the etched cross-section sample. The cross-sectional sample shows that no porosity was present in the welded region or any crack or other type of welding defect and that a sound weld joint was formed after laser welding.

The weld bead in the cross-section can be seen to approx. 2.15 mm which is slightly less than the top side of the sample which is about 2.25 mm. The difference can be a result of the laser beam. As the laser beam penetrates from the top to bottom, the top of the sample faces the maximum power of the laser beam and hence has a higher weld bead dimension whereas the beam loses some power when penetrating the sample, hence, the weld bead decreases in size although the difference is only of 0.1 mm approximately.

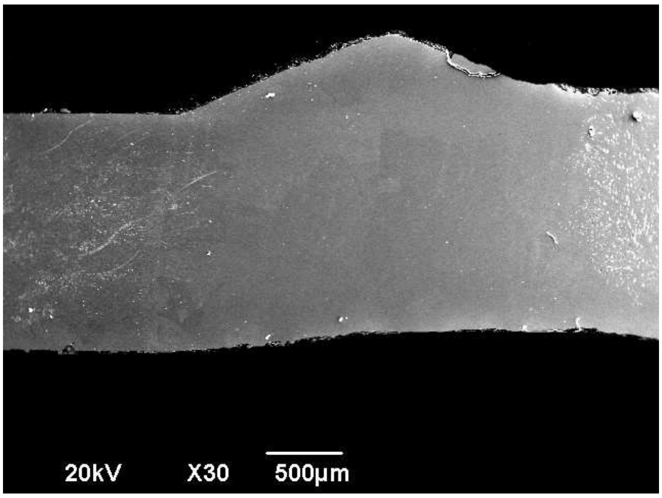

Fig. 3. SEM image of a cross-section of the welded sample.

3.3. Radiography

The examination after radiography revealed that the welded joints were free from defects like cracks, undercuts, porosity, slag inclusion, incomplete root penetration, insufficient fusion, etc. The radiographic film presented in the figure below illustrates the quality of the welded joints.

Fig. 4. Radiography film of welded sample

3.4. Micro Vicker Hardness

Hardness testing was performed on the welded sample on the cross-section. The sample was first mounted and then polished before hardness testing. The result of testing at 200gf for 10 sec applied load is given in the table below.

Table 1. Average Micro Hardness Results of Welded HEA and SS 304 Sample in HV

HEA	HAZ1	Weld Zone	HAZ2	SS 304
154.2	166.0	154.6	222.5	209.6

Hardness measurements were conducted at 0.1 mm intervals until a constant reading was achieved in the base metals. The heat-affected zone (HAZ) on both sides was approximately 0.2 mm, notably less than gas tungsten arc welding of Cantor alloy with SS 304 (about 1.2 mm) reported by Zhang, 2023. In contrast, the welding of Cantor alloy with duplex stainless steel exhibited a HAZ of 0.5-0.75 mm as reported by N. K. Adomako, 2021 [1]. Subsequent etching of the weld zone (WZ) allowed for indentation verification, enhancing the assessment of hardness properties in the WZ and HAZ.

Analysis indicated that the weld zone had the lowest hardness, while SS 304 in a rolled condition exhibited the highest, attributed to strain-induced martensite. The HAZ displayed a hardness trend near the base metals like the weld zone, consistent with observations by Zhang, 2023 [6]. The elevated hardness in HAZ can be explained by grain size refinement in the HAZ, leading to finer grains compared to HEA and SS 304 base metals. The relationship between hardness (H) and grain size (d) follows the equation mentioned below.

$$H = H_o + K / \sqrt{d} \quad (1)$$

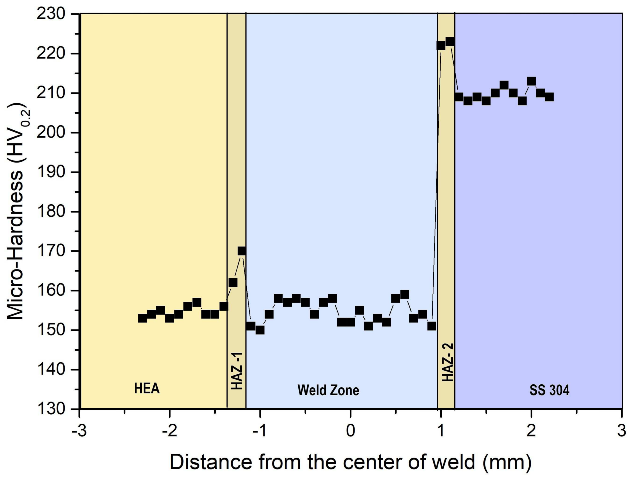

Fig. 5. Micro Hardness Profile of HEA/SS Sample.

An increase in grain size adjacent to the fusion line, attributed to the HAZ acting as a thermal treatment, led to decreased hardness as mentioned by Laplanche, 2015 [8]. This transition is due to a lower heat treatment temperature near the base material, resulting in a marginal hardness increase, while closer to the fusion line, higher temperatures cause a decrease in hardness. The WZ exhibited slightly higher hardness values than HEA due to the hardening effect of refined equiaxed grains, with hardness near the fusion zone boundary slightly less than at the centreline, explained by the presence of a larger columnar crystal structure. See the image for the cross-sectional view of the etched hardness sample.

Fig. 6. Cross-sectional optical image of sample after micro-Vickers hardness testing.

4. Conclusion

In conclusion, this research has undertaken a comprehensive investigation into the dissimilar laser welding of High Entropy Alloy (HEA), FeNiMnCr18, and Stainless Steel 304 (SS 304). The utilization of advanced techniques, coupled with optimized parameters, has resulted in the successful creation of defect-free welds, as affirmed by meticulous examinations encompassing mechanical testing, microstructure characterization, and radiography. The micro-Vickers hardness profile has provided valuable insights into the nuanced variations in hardness across different zones of the welded joint. Beyond the technical aspects, this study holds significance in advancing the understanding of dissimilar welding involving HEAs and conventional alloys. The observed trends in grain growth, and mechanical properties (hardness of 154.6 HV in weld zone) contribute to a holistic comprehension of the welding process. Moreover, the findings of this research extend beyond the laboratory, suggesting potential applications in critical structural scenarios. The optimized laser welding parameters and the significance of shielding gases underscore the practical implications of this work, offering avenues for further research and technological applications in the field of material science and welding technology.

Acknowledgments

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References

[1] Adomako, N. K., Shin, G., Park, N., Park, K., & Kim, J. H., 2021. Laser dissimilar welding of CoCrFeMnNi-high entropy alloy and duplex stainless steel. Journal of Materials Science & Technology, 85, p. 95-105.

[2] Wu, Z., Bei, H.,2015. Microstructures and mechanical properties of compositionally complex Co-free FeNiMnCr18 FCC solid solution alloy. Materials Science and Engineering: A, 640, p. 217-224.

[3] Kumar, N. A. P. K., Li, C., Leonard, K. J., Bei, H., Zinkle, S. J., 2016. Microstructural stability and mechanical behavior of FeNiMnCr high entropy alloy under ion irradiation. Acta Materialia, 113, p. 230-244.

[4] Hafez, K. M., 2023. The influence of shielding gases on keyhole-induced porosity and nitrogen absorption in SS 304 stainless steel fiber laser welds. The International Journal of Advanced Manufacturing Technology, 127(3), p. 1887-1894.

[5] Oliveira, J. P., Shen, J., Zeng, Z., Park, J. M., Choi, Y. T., Schell, N., . . . Kim, H. S., 2022. Dissimilar laser welding of a CoCrFeMnNi high entropy alloy to 316 stainless steel. Scripta Materialia 206, p. 114219.

[6] Zhang, P., Qi, Y., Cheng, Q., Sun, X., 2023. Welding Dissimilar Alloys of CoCrFeMnNi High-Entropy Alloy and 304 Stainless Steel Using Gas Tungsten Arc Welding. Journal of Materials Engineering and Performance.

[7] Katayama, S., 2013. Handbook of Laser Welding Technologies, p. 1-632

[8] Laplanche, G., Horst, O., Otto, F., Eggeler, G., George, E. P., 2015. Microstructural evolution of a CoCrFeMnNi high-entropy alloy after swaging and annealing. Journal of Alloys and Compounds, 647, p. 548-557.