Effect of Process Parameters on Interfacial Temperature and Shear Strength of Ultrasonic Additive Manufacturing of Carbon Steel 4130

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Ultrasonic additive manufacturing (UAM) is a solid state manufacturing process capable of producing near-net-shape metal parts. Recent studies have shown the promise of UAM welding of steels. However, the effect of weld parameters on the weld quality of UAM steel is unclear. A design of experiments study based on a Taguchi L16 design array was conducted to investigate the influence of parameters including baseplate temperature, amplitude, welding speed, and normal force on the interfacial temperature and shear strength of UAM welding of carbon steel 4130. Analysis of variance (ANOVA) and main effects analyses were performed to determine the effect of each parameter. A Pearson correlation test was conducted to find the relationship between interfacial temperature and shear strength. These analyses indicate that a maximum shear strength of 392.8 MPa can be achieved by using a baseplate temperature of 400°F (204.4°C), amplitude of 31.5 μm, welding speed of 40 in/min (16.93 mm/s), and normal force of 6000 N. The Pearson correlation coefficient is calculated as 0.227, which indicates no significant correlation between interfacial temperature and shear strength over the range tested.
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1 Introduction

Ultrasonic additive manufacturing (UAM) is an emerging solid-state rapid manufacturing process for producing near-net-shape metal parts. Additive ultrasonic metal welding and CNC subtractive machining stages are combined in the UAM machine. During the UAM welding process, a normal force and ultrasonic (20 kHz) transverse vibrations are applied to metal foils and produce localized plastic deformation to form metallurgical bonds at the interface. This welding process is repeated either next to, or on top of, the preceding layer of foils to build up a component. Then, the subtractive stage is used to selectively remove material and machine the component to its final dimensions [1,2]. It can also be employed to make internal features such as channels for embedding reinforcement fibers [3] and thermally sensitive smart materials [4].

Previous studies have demonstrated that the weld quality of UAM builds depends sensitively on the selection of process parameters [5–7]. Most of these studies focused on the process development of aluminum alloys and assessed the weld quality with mechanical tests including peel [8], tensile, shear, and push-pin as well as microstructure analyses including linear weld density (LWD). However, less attention has been paid to UAM welding of high strength steel because of the lack of fundamental understanding of the UAM process as well as certain equipment limitations [9–11]. In the early stage of UAM steel welding research, one case study was reported to investigate the effect of normal force, vibration amplitude, and welding speed on the weld quality of UAM stainless steel 316L. However, no mechanical properties of UAM-fabricated SS 316L builds were provided [12].

Recent advances in the UAM process have allowed a higher ultrasonic power input for UAM steel welding without creating any adhesive wear, which makes it possible to achieve a high strength UAM weld with steel. However, the influence of each process parameter on the weld quality of UAM steel is unclear. There is evidence that an elevated interfacial temperature is critical for achieving UAM steel builds with a higher mechanical strength [13]. But, the relationship between UAM steel interfacial strength and interfacial temperature has not been investigated. Consequently, a design of experiments (DOE) study was developed to explore the dependence of UAM steel weld quality and peak interfacial temperature on UAM process parameters including normal force, vibration amplitude, baseplate temperature, and welding speed. The UAM steel weld quality is characterized using a custom shear test method and the peak interfacial temperature is measured using a K-type thermocouple. The statistical relationship between the UAM steel shear strength and peak interfacial temperature is also analyzed by using Pearson correlation.

2 Experimental Methods

2.1 Sample Fabrication. The materials used in this study are 0.127 mm (0.005 in.) thick, 25.4 mm (1.0 in.) wide annealed AISI 4130 steel foils and low carbon ASTM A36 steel baseplates. AISI

Table 1 Taguchi L16 design array used for DOE where 1 indicates the lowest and 4 indicates the highest level for each parameter

Parameter set (PS)	Baseplate temperature	Amplitude	Welding speed	Normal force
PS1	1	1	1	1
PS2	1	2	2	2
PS3	1	3	3	3
PS4	1	4	4	4
PS5	2	1	2	3
PS6	2	2	1	4
PS7	2	3	4	1
PS8	2	4	3	2
PS9	3	1	3	4
PS10	3	2	4	3
PS11	3	3	1	2
PS12	3	4	2	1
PS13	4	1	4	2
PS14	4	2	3	1
PS15	4	3	2	4
PS16	4	4	1	3

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Table 2 Weld parameter values for each DOE level

Parameter	Level 1	Level 2	Level 3	Level 4
Baseplate temperature	100 °F (37.8 °C)	200 °F (93.3 °C)	300 °F (148.9 °C)	400 °F (204.4 °C)
Amplitude	27.1 μm	28.57 μm	30.03 μm	31.5 μm
Welding speed	40 in/min (16.93 mm/s)	60 in/min (25.40 mm/s)	80 in/min (33.87 mm/s)	100 in/min (42.33 mm/s)
Normal force	4000 N	5000 N	6000 N	7000 N

4130 steel was selected because of its heat treatability and frequent use in industry. All UAM samples were manufactured using a 9 kW Fabrisonic SonicLayer 4000 UAM system with a cobalt-chromium coated tool steel sonotrode. Three shear test samples were prepared for each treatment condition. Each shear test sample was made from 12 layers of annealed 4130 steel foil and an A36 steel baseplate, while each temperature measurement sample was made from three layers of annealed 4130 steel foil and an A36 baseplate.

Even though a full factorial DOE can provide more detailed analyses [14], the extra cost and time associated with it make it less desired. Thus, an economic method Taguchi design is used in this study. The weld parameters for this DOE study follow a Taguchi L16 matrix design with four parameters: normal force, vibration amplitude, baseplate temperature, and welding speed. The Taguchi L16 matrix design reduces the total number of treatment combinations from 256 to 16 for a design including four parameters at four levels each. The matrix design was generated with Minitab statistical software (Minitab Inc., State College, PA) and is presented in Table 1, where 1 indicates the lowest level and 4 indicates the highest level for each parameter. The exact value for each level of each parameter was determined from a pilot study. The lower limits for weld parameters (baseplate temperature of 100 °F (37.8 °C), amplitude of 27.1 μm, welding speed of 100 in/min (42.33 mm/s), and normal force of 4000 N) are the values below which welds could not be achieved, and the upper limits for weld parameters (a baseplate temperature of 400 °F (204.4 °C), amplitude of 31.5 μm, welding speed of 40 in/min (16.93 mm/s), and normal force of 7000 N) are the values above which the top of the steel foil becomes welded to the sonotrode. The values selected for each parameter and level are shown in Table 2.

Pilot studies showed that 4130 steel foils would not weld to the A36 baseplate using certain sets of weld parameters. Consequently, all first layers were welded using the same set of parameters (Table 3) to provide a consistent base for the foil-to-foil welds being investigated. All of the subsequent foil layers were welded using the DOE study parameters presented in Table 2. The shear test is designed to shear the interface between the second and third layers of steel foil and the temperature is measured at the same interface during welding.

2.2 Temperature Measurements. An OMEGA Type K AWG40 thermocouple (0.080 mm tip diameter) was used to measure the temperature at the interface between the second and third layers of steel foil during welding. Before measurement, a 1.5 mm hole was drilled through the baseplate. Next, two layers of steel foil were welded onto the baseplate and a 1.5 mm hole was pierced through the foils at the location of the original hole. Finally, a thermocouple was placed through the hole and bent on the top surface of the foil. A schematic of the experimental setup is shown in Fig. 1. Interfacial temperature was measured at 10 kHz while the third layer of foil was welded onto the preceding foil layer. Temperature was measured twice for each treatment.

2.3 Mechanical Testing. A custom shear test method was used to characterize the mechanical strength of the interface between the second and third layers of UAM steel builds. This interface is selected to represent the foil-foil welding strength. The interface between the first and second layers is too close to the baseplate and not selected to prevent any undesired failure at the baseplate-foil interface. A stepped sample geometry is used in this study to ensure that shearing occurs at the desired interface. The sample geometry and loading conditions are shown in Figs. 2(*a*) and 2(*b*). The shear test was performed on an MTS C43.504 50 kN load frame and fixed between two compression platens as shown in Fig. 2(*c*). The tests are conducted using displacement control with a loading speed of 0.02 mm/s.

2.4 Statistical Procedures. The statistic model used in this study was a generalized linear model (GLM) with four main effects. The linear model is given by

$$Y_{ijklt} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + \varepsilon_{ijklt} \quad (1)$$

This equation describes the dependence of the response variable (shear strength or interfacial temperature), Y_{ijklt}, on the levels of the treatment factors. In this equation, μ is the overall mean of the response variable (shear strength or interfacial temperature). The effects of the weld parameters are represented by α_i, β_j, γ_k, and δ_l, where α_i denotes the effect of baseplate temperature at the ith level when the other parameters are fixed. Similarly, β_j, γ_k, and δ_l represent the effects of amplitude, weld speed, and normal force at the jth, kth, and lth levels, while the other parameters are fixed.

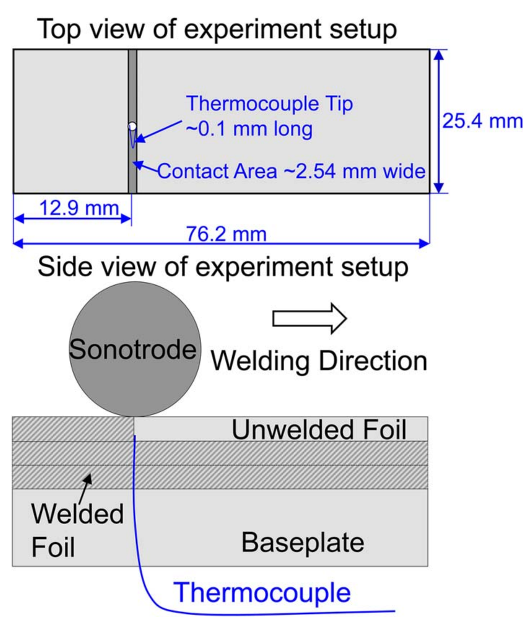

Fig. 1 Schematic of temperature measurement setup with the embedded thermocouple

Table 3 Weld parameters used for welding first layer

Parameter	Level
Baseplate temperature	400 °F (204.4 °C)
Amplitude	28.57 μm
Welding speed	80 in/min (33.87 mm/s)
Normal force	5000 N

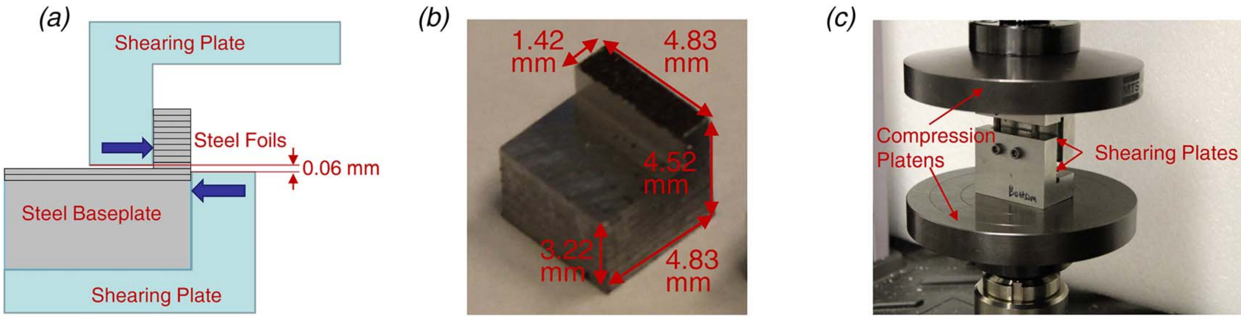

Fig. 2 Shear test design includes (*a*) conceptual schematic of shear test loading condition, (*b*) image of shear test sample with nominal dimensions, and (c) image of experimental setup of the shear test with loaded sample on load frame

Table 4 Interfacial temperature measurements for representative low peak temperature (PS9) and high peak temperature (PS16) samples

Sample	PS9	PS16
1	548 °C	921 °C
2	547 °C	878 °C
Mean	548 °C	900 °C

The error variable, ε_{ijklt}, is a variable with normal distribution and zero mean which denotes any nuisance variation in the response. All ε_{ijklt} are mutually independent with respect to *i*, *j*, *k*, *l*, and *t*.

After shear tests and temperature measurements were completed, analysis of variance (ANOVA) was first performed to determine the statistical significance of each parameter with respect to the response variables. Then, main effects plots were used to further analyze the effect of each parameter and to indicate the optimal levels of the parameters for shear strength within the current process window.

3 Results

3.1 Temperature Measurement and Shear Test. Representative temperature measurement plots for a low peak temperature and a high peak temperature are shown in Table 4 and Fig. 3, where PS16 produces a high peak temperature and PS9 gives a low peak temperature. Due to the different speeds for the different parameter sets, the sonotrode was centered over the thermocouple at 0.38 s and 0.76 s for PS9 and PS16, respectively, as indicated in Fig. 3. Additional details regarding the temperature profile can be found in Ref. [13].

Similarly, representative shear test results for a poor weld and a good weld are shown in Table 5 and Fig. 4. In this study, a poor weld is defined as a weld that possesses a shear strength less than 60% of the bulk 4130 material [15]. A good weld is defined as a weld that possesses a shear strength greater than 60% of the bulk 4130 material. PS9 generates a poor weld and PS11 yields a good weld. It is also worth noting that three samples were intended to be tested for each condition. Forty-eight shear samples were intended to be made, however twelve of them for different treatment combinations failed during machining and preparation. For the data presented in Table 5 and Fig. 4, one shear sample for PS11 failed before testing. Thus, no data was obtained for that sample.

The interfacial temperature and shear strength measurements for each parameter set are presented in Table 6. As shown, the highest peak temperature of 900°C and the highest shear strength of 392.8 MPa are produced by the same parameter set, PS16. The lowest shear strength of 0 MPa results from PS1, while the lowest peak temperature of 427 °C is reached with PS13.

3.2 Statistical Analysis of Interfacial Temperature. An ANOVA with interfacial peak temperature as the response variable was studied first. The variability in the shear test results was

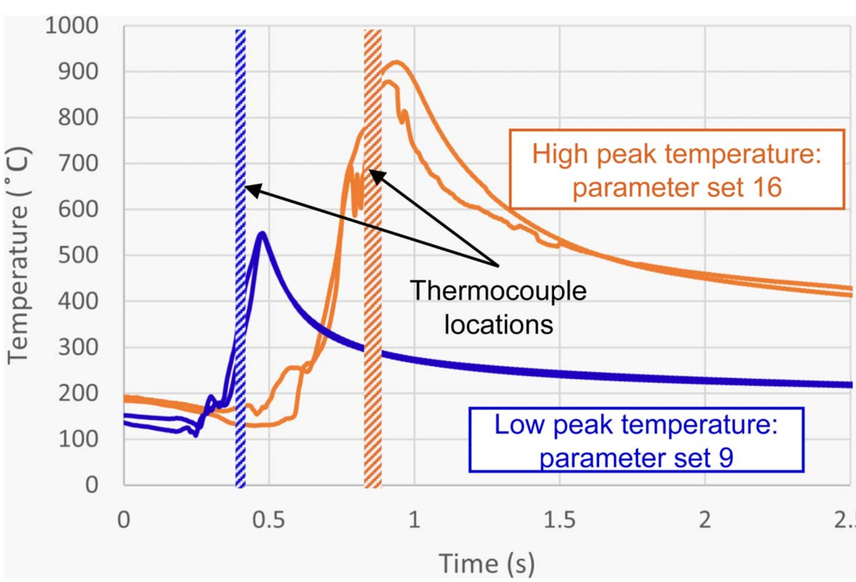

Fig. 3 Representative interfacial temperature measurement plots with thermocouple locations indicated by the dashed patterns

Table 5 Shear test results for representative bad weld (PS9) and good weld (PS11) samples

	PS9		PS11	
Sample	Max force (N)	Max shear strength (MPa)	Max force (N)	Max shear strength (MPa)
1	958.1	138.5	2583.0	366.6
2	759.4	111.8	2754.4	382.1
3	891.2	131.2	N/A	N/A
Mean	869.6	127.1	2668.7	374.4

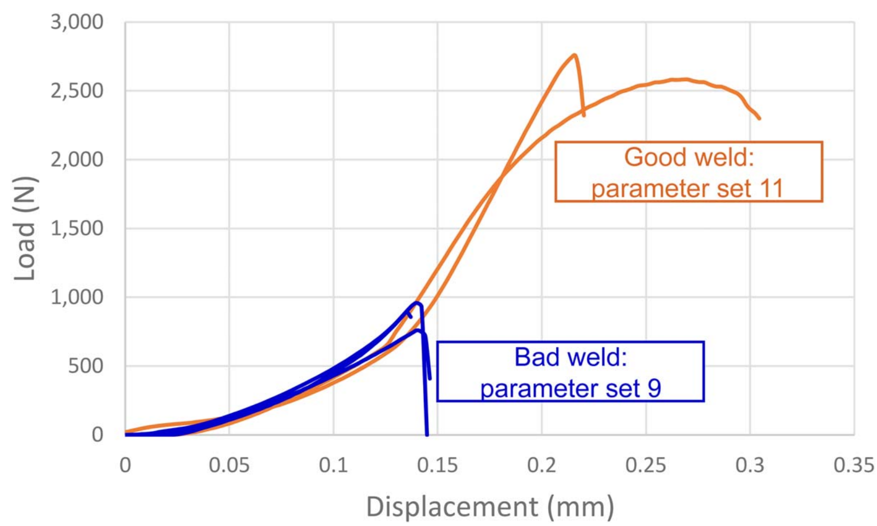

Fig. 4 Representative shear test load-displacement curves

partitioned into model effects and random error. The adjusted type I error probability, alpha, selected for this experiment was 0.05 to test each of the weld parameters. This alpha level is the threshold probability that the null hypothesis is rejected due to a false positive error (type I error). The p-value is the probability of obtaining a test at least as extreme as the observation, assuming that the null hypothesis of no effect is true. Lower p-values indicate stronger evidence against the null hypothesis. When the p-value is less than alpha, the null hypothesis is rejected in favor of the alternative hypothesis. In this study, the ANOVA was performed using MINITAB statistical software (Minitab Inc., State College, PA). As shown in Table 7, amplitude, welding speed, and normal force are considered statistically significant with p-values less than 0.05. Baseplate temperature is the only parameter that is considered insignificant with a p-value above 0.05. The main effects plots agree with the ANOVA as shown in Fig. 5. The baseplate temperature plot shows that interfacial temperature stays nearly the same for levels 1, 2, and 3. The interfacial temperature increases further as baseplate temperature increases from level 3 to 4. Increasing the amplitude increases the interfacial temperature in general, despite a slight decrease when increasing from level 2 to 3. In contrast, the interfacial temperature increases as the welding speed decreases. The normal force exhibits a mixed impact on the interfacial temperature. The interfacial temperature is higher at levels 1 and 4 than at levels 2 and 3 for normal force.

Table 6 Interfacial temperature and shear strength measurements for each parameter set

Parameter set (PS)	Peak interfacial temperature (°C)	Shear strength (MPa)
PS1	727	0
PS2	725	129.3
PS3	595	187.7
PS4	601	191.8
PS5	459	258.2
PS6	849	205.1
PS7	645	196.7
PS8	703	248.7
PS9	548	127.1
PS10	471	233.0
PS11	700	374.4
PS12	817	162.3
PS13	427	141.4
PS14	729	162.3
PS15	782	206.5
PS16	900	392.8

3.3 Statistical Analysis of Shear Test. The dependence of shear strength on the weld parameters was also analyzed by ANOVA. As shown in Table 8, amplitude and normal force have a statistically significant effect on shear strength, with p-values

Table 7 ANOVA using interfacial temperature as response variable

Source	DF	Adj SS	Adj MS	F-value	P-value
Baseplate temperature	3	23,244	7748	3.05	0.054
Amplitude	3	198,181	66,060	26.02	0.000
Welding speed	3	277,357	92,452	36.41	0.000
Normal force	3	73,427	24,476	9.64	0.000
Error	16	48,245	2539	•	•
Total	31	620,454	•	•	•

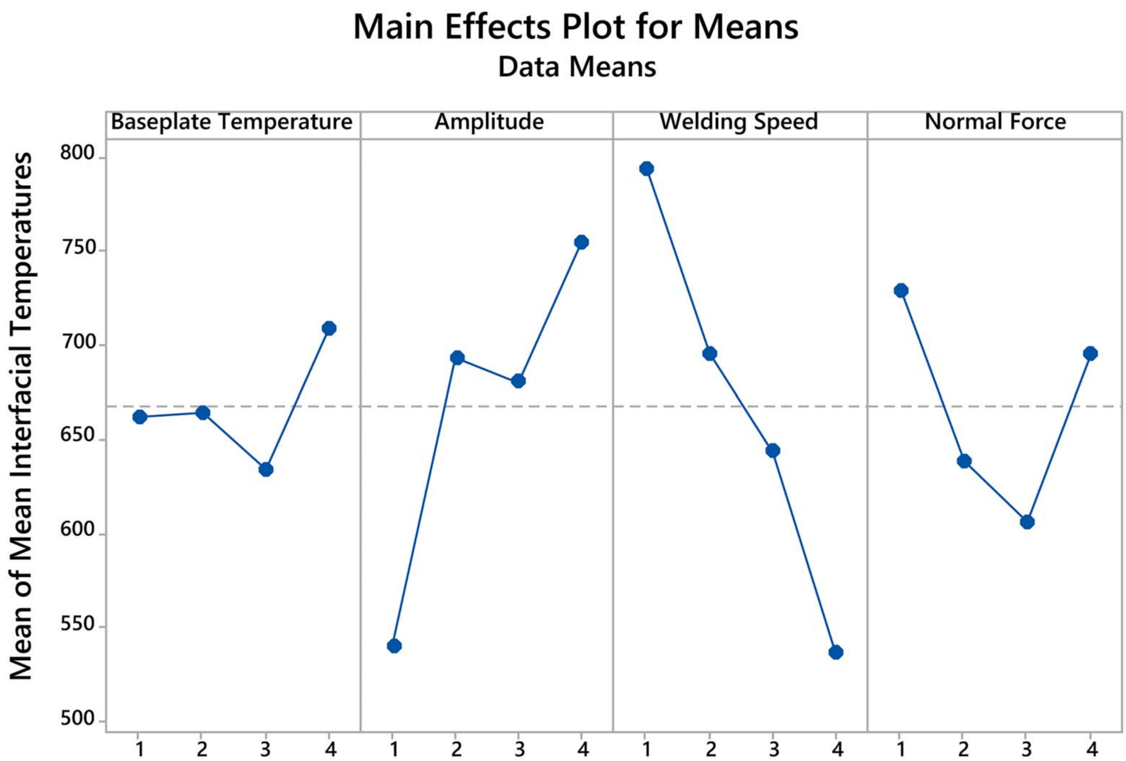

Fig. 5 Main effects plots for interfacial temperature

Table 8 ANOVA using shear strength as response variable

Source	DF	Adj SS	Adj MS	F-value	P-value
Baseplate temperature	3	9591	3197	0.94	0.44
Amplitude	3	34,001	11,334	3.32	0.04
Welding speed	3	23,351	7784	2.28	0.109
Normal force	3	31,653	10,551	3.09	0.049
Error	21	71,655	3412	•	•
Total	33	229,496	•	•	•

less than 0.05. Baseplate temperature and welding speed are considered insignificant with p-values greater than 0.05.

To further investigate the effect of weld parameters, main effects plots are analyzed and provided in Fig. 6. The baseplate temperature plot shows that the lowest level 1 exhibits the smallest shear strength. Increasing baseplate temperature from level 1 to level 2 increases the shear strength. However, further increasing the baseplate temperature generates very little change in response. The flat pattern for levels 2, 3, and 4 explains why baseplate temperature is not statistically significant with a p-value greater than 0.05. The amplitude plot shows a continuous increase in shear strength with increasing amplitude, which agrees with the ANOVA results. The increase in response is minimal when increasing from level 1 to 2 or from level 3 to 4. The increase is more significant when increasing from level 2 to 3. The shear strength decreases significantly when the welding speed increases from level 1 to level 2. The shear strength stays nearly the same when welding speed further increases from level 2 to level 4. The normal force reaches a peak at level 3 and the plot trend is different than those for other parameters.

4 Discussion

As the ANOVA and the main effects plots show, amplitude was found to be one of the most influential parameters for both interfacial temperature and shear strength. Increasing amplitude enhances the scrubbing action which collapses asperities and disperses oxides and contaminants at the interface. These actions lead to localized plastic deformation, which is favorable for the formation of strong metal welds. The heat generated from the scrubbing actions and local plastic deformation increases interfacial temperature. However, it is expected that as amplitude increases beyond a certain upper threshold, excessive plastic deformation may occur at the interface and lead to increased void density, which causes a decrease in shear strength.

Normal force was also found to have a significant effect on both interfacial temperature and shear strength. This result is different from the findings for UAM Al 6061 [5], which may be due to the hardness difference between Al alloys and high strength steel. The steel requires higher normal force to reach a maximum compression point at which no more asperities can collapse. The difference in material properties and normal force ranges may contribute to the different effects on interfacial temperature and shear strength.

Welding speed was found to be statistically significant for interfacial temperature, but insignificant for shear strength. With other parameters set the same, a slower welding speed allows higher energy input at the interface, which generates more heat during the welding process. It is found that increasing the welding speed from 40 in./min (16.93 mm/s) to 60 in./min (25.40 mm/s) has a significant negative effect on shear strength. However, the shear strength stays nearly the same when changing the welding speed from 60 in./min (25.40 mm/s) to 80 in./min (33.87 mm/s) or 100 in./min (42.33 mm/s). This indicates that the upper threshold for making a strong UAM 4130 steel weld within the process window investigated is between 40 in./min (16.93 mm/s) and 60 in/min (25.40 mm/s). Beyond that point, the shear strength would decrease significantly and then stay nearly the same when continuing to increase the welding speed.

Baseplate temperature was found to be an insignificant factor for both interfacial temperature and shear strength. The interfacial temperature is caused by the heat input from the baseplate and the heat generated during welding. Since the heat input to the welding interface from the baseplate is much lower than the heat generated from friction and plastic deformation during welding, the baseplate

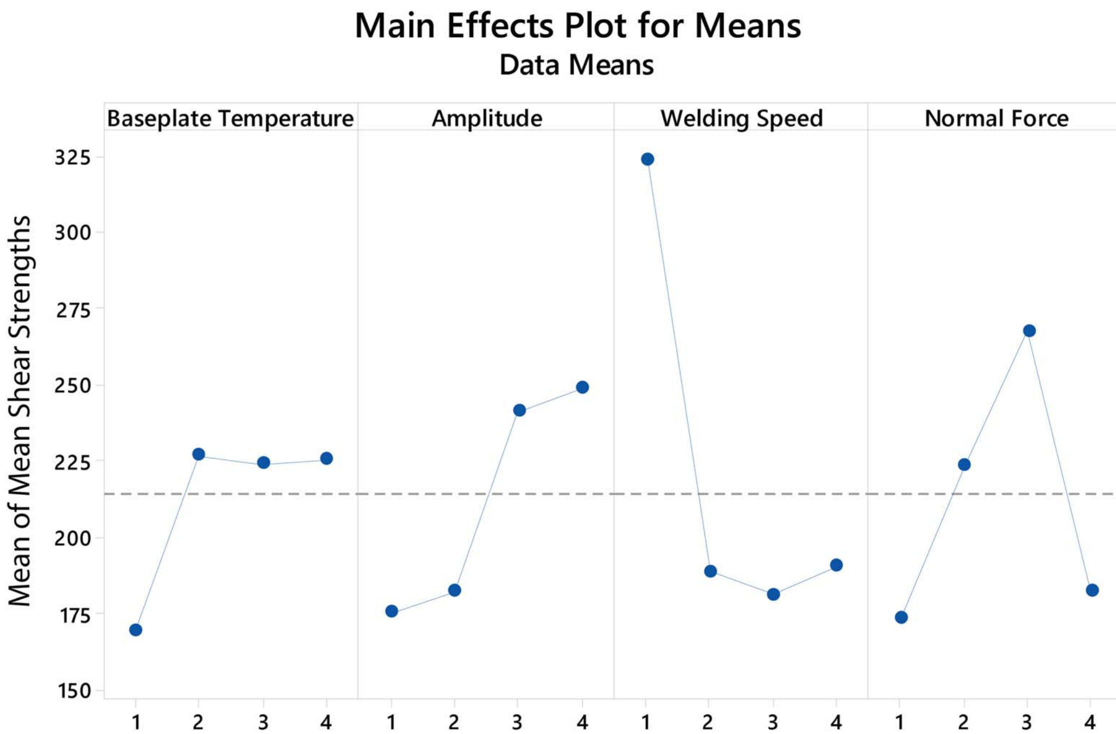

Fig. 6 Main effects plots for shear strength

temperature is expected to have a smaller effect on the interfacial temperature. In a recent study [9], the baseplate temperature is found to be critical for achieving a high strength baseplate-foil weld. However, that statement may not hold for foil-foil welding, which is investigated in this study. In the pilot study for finding viable parameters, the parameter combinations listed in the DOE table were used for welding the first layer of foil to the baseplate. However, all the treatment combinations with lower baseplate temperatures 100°F (37.8°C) or 200°F (93.3°C) generated no welds or weak welds that could be easily peeled off by hand.

The relationship between interfacial temperature and shear strength is studied. The Pearson correlation coefficient is found to be 0.227, which indicates no significant correlation between the two response variables [16]. This analysis indicates that interfacial temperature may affect the shear strength of a foil-foil weld interface. However, other factors may play a more influential role in achieving a high shear strength weld.

In this DOE study, the main effects of four process parameters on the interfacial temperature and shear strength were investigated. However, one limit of the Taguchi L16 array used in the study is that this design does not allow analysis of interaction terms due to the limited degrees-of-freedom. To better quantify interactions among effects, a different DOE design should be explored in the future. More advanced statistical techniques such as the response surface method can be used to optimize the process parameters and determine the optimum shear strength. The parameters used and studied in this paper should serve as a reference for a more detailed optimization study.

5 Conclusions

A design of experiments study using a Taguchi L16 design array was carried out on carbon steel 4130 to investigate the effect of weld parameters including baseplate temperature, amplitude, welding speed, and normal force on the interfacial temperature and shear strength. Analysis of variance and main effects plots show that normal force and amplitude have a statistically significant effect on shear strength, while similar analyses show that normal force, amplitude, and welding speed are significant for interfacial temperature. The Pearson correlation coefficient is calculated as 0.227, which indicates no significant correlation between interfacial temperature and shear strength over the range tested. We conclude that interfacial temperature cannot be used by itself as a strong indicator of weld quality. Within the selected process window, the following combination of process parameters tested in this DOE study generates the highest shear strength: baseplate temperature of 400°F (204.4°C), amplitude of 31.5 μm, welding speed of 40 in/min (16.93 mm/s), and normal force of 6000 N.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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