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EXPLORING THE INFLUENCE OF HEAT INPUT ON SMAW WELD BEAD GEOMETRY: ANALYZING PENETRATION, REINFORCEMENT, AND BEAD WIDTH RELATIONSHIPS

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ABSTRACT

This study investigates the critical relationship between heat input and key aspects of weld bead geometry, specifically focusing on penetration, reinforcement, and bead width. Understanding these relationships is essential for optimizing welding processes to achieve desired mechanical properties and structural integrity. Through a series of controlled welding experiments, we analyze how varying heat inputs affect the depth of penetration, the height of reinforcement, and the width of the weld bead. Our findings demonstrate that increased heat input generally results in deeper penetration and a broader bead width, while its effect on reinforcement height is more complex and dependent on the balance between amprage and welding speed. The study provides valuable insights into the delicate balance required to optimize heat input for SMAW *welding applications, highlighting the trade-offs that must be managed to achieve optimal weld quality. These insights can inform welding process adjustments to improve the performance and reliability of welded joints in various industrial applications.*

Keywords: SMAW Welding, bead geometry, heat input, penetration, reinforcement.

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1. Introduction

Welding is a critical fabrication technique employed across various industries, including construction, automotive, and aerospace. The efficiency and effectiveness of welding processes can greatly depend on parameters such as heat input, which influences both the mechanical properties of the welded materials and the geometric characteristics of the weld bead itself, ultimately affecting the structural integrity of the final product. The relationship between heat input and the resultant weld bead geometry, particularly regarding factors such as penetration, reinforcement, and bead width, necessitates thorough investigation since variations in these parameters can lead to significant changes in the weld's performance characteristics and its ability to withstand applied loads [1].

Recent advancements in welding techniques, such as the development of waveform-controlled short arc welding processes with low heat input, have shown promise in addressing the challenges associated with welding thin components while maintaining stability and reducing spatter formation [2]. Moreover, the management of heat input is reported to be critical in influencing the temperature distribution within the weld pool, which directly correlates with grain structure alterations in the heat-affected zone and can lead to variations in mechanical properties such as tensile strength and hardness. Similarly, studies have highlighted the significant impact of heat input on the residual stresses and distortion in high-strength steel components produced through wire-arc additive manufacturing processes [1], underscoring the need for a comprehensive understanding of the heat input-weld bead geometry relationship [1,2].

To better understand the influence of heat input on weld bead geometry, this study aims to analyze the relationships between heat input and the key characteristics of the weld bead, including penetration, reinforcement, and bead width. By systematically varying heat input parameters and measuring the resulting bead dimensions and penetration depth, we can elucidate how these factors interact and affect the overall quality and structural performance of welds, providing insights that can enhance welding practices in various applications [3].

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Recent advancements in welding techniques, such as the development of waveform-controlled short arc welding processes with low heat input, have shown promise in addressing the challenges associated with welding thin components while maintaining stability and reducing spatter formation. Moreover, the management of heat input is reported to be critical in influencing the temperature distribution within the weld pool, which directly correlates with grain structure alterations in the heat-affected zone and can lead to variations in mechanical properties such as tensile strength and hardness. Similarly, studies have highlighted the significant impact of heat input on the residual stresses and distortion in high-strength steel components produced through wire-arc additive manufacturing processes, underscoring the need for a comprehensive understanding of the heat input-weld bead geometry relationship. This study aims to further explore the influence of heat input on the geometric characteristics of the weld bead, including penetration, reinforcement, and bead width, in order to provide insights that can guide welding parameter optimization and improve the overall quality and performance of welded structures. To achieve this, a series of experimental welding trials will be conducted, systematically varying the heat input while measuring the outcome on weld bead characteristics, thereby allowing for a detailed analysis of their interdependencies and resulting implications for material performance and structural integrity [1].

While numerous studies have analyzed individual bead characteristics under varying heat input, few have provided a comprehensive correlation of penetration, width, and reinforcement with quantified parametric variation in SMAW under consistent environmental and material conditions.

2. Methodology

The comparative analysis was conducted by performing SMAW welds beads in controlled conditions. Welding parameters such as voltage, electrode type, and polarity, welding speed were standardized for consistency. Optimal parameters for achieving high-quality welds in wet environments include a welding speed of 288 mm/min, the arc current rabge from 89 to 105 A, and an electrode angle of 90° and 10° travel angle. These parameters balance bead penetration, morphology, and mechanical properties. Table 1 explain weld parameters.

Table 1: Experiment parameters

Variable	Measure
Welding current	89 - 105A
Voltage	22-23
Travel speed	288 mm/min
Current/ Polarity	DCEN
Electrode	AWS Classification - E6013
	Specification SFA 5.1
	Filler Metal F-No 6
	Size of Filler Metals 2.4 mm
Base metal QW/QB-422	Material specification SA-36
	P-1
	Group 1
	Thickness of 6 mm

To investigate the relationship between heat input and weld bead geometry, a series of experiments were conducted using the Shielded Metal Arc Welding process, a commonly employed welding technique in various industries. 16 samples were prepared with varying heat input levels, achieved by adjusting parameters such as welding current and travel speed, and the resulting weld beads were analyzed for penetration (P) or depth, bead width (W), and reinforcement (R) or height to determine the correlations between these factors and the applied heat input.

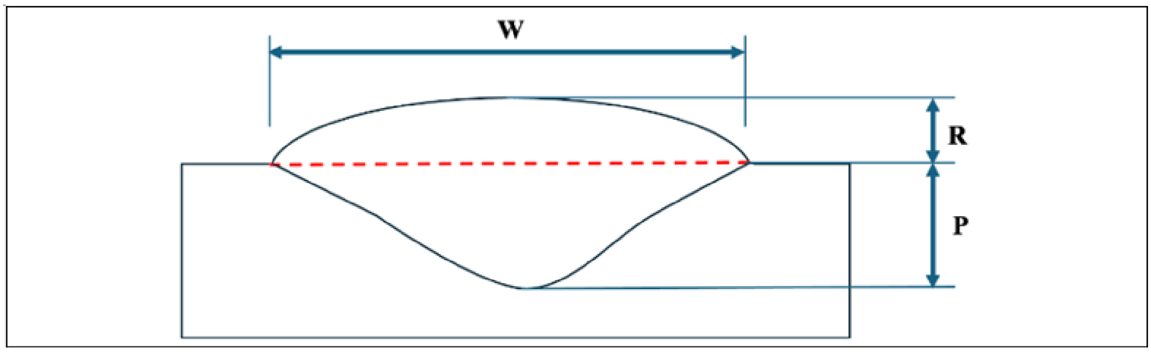

Figure 1: Weld bead geometry of SMAW samples

The experiments were carried out in a controlled laboratory environment. In addition, the experimental setup involved the use of E6013 welding rods and A36 steel base materials to evaluate the generalized effects of heat input across bead geometry, thereby allowing for a comprehensive analysis of how varying parameters influence the resultant bead geometry and overall weld quality [1,5].

Heat input in welding is a crucial parameter that significantly influences the characteristics of the weld, including its microstructure, mechanical properties, and overall geometry. It refers to the amount of energy delivered to the workpiece during the welding process, which affects the temperature distribution, cooling rate, and the extent of fusion in the base material. The heat input is typically calculated using the formula:

Heat Input = (60 x Amps x Volts) / (1000 x Travel Speed in mm/min)	Equation 1 [6] (AWS 2001)

where:

Voltage (V): is the electrical potential difference applied across the welding arc.

Current (I): is the flow of electric charge through the welding circuit, typically measured in amperes (A).

Welding Speed (S): is the rate at which the welding electrode or torch moves along the joint, usually measured in millimeters per minute (mm/min) or inches per minute (ipm).

The result of this calculation gives the heat input in joules per millimeter (J/mm), indicating the energy deposited per unit length of the weld. Controlling heat input is essential to prevent defects such as excessive distortion, cracking, or incomplete fusion, and to achieve the desired balance between penetration, reinforcement, and bead width. By adjusting the welding parameters, such as voltage, current, and speed, welders can fine-tune the heat input to optimize weld quality for different materials and applications.

3. Results and Discussion

The experimental data collected during the study revealed several key findings regarding the influence of heat input on weld bead geometry:

As the heat input was increased, the penetration depth of the weld bead exhibited a positive correlation, with higher heat input levels resulting in greater penetration into the base material as shown in figure 2. This trend aligns with Casas et al. [5] observations, where alterations in heat input were found to significantly impact the extent of weld penetration, highlighting the importance of optimizing this parameter for achieving desired mechanical properties and joint integrity in welded structures [1]. In contrast, excessively high heat input can lead to undesirable effects such as excessive bead reinforcement and wider bead dimensions, which may contribute negatively to the overall mechanical performance of the weld, emphasizing the need for precise control of these parameters in the welding process [1,4].

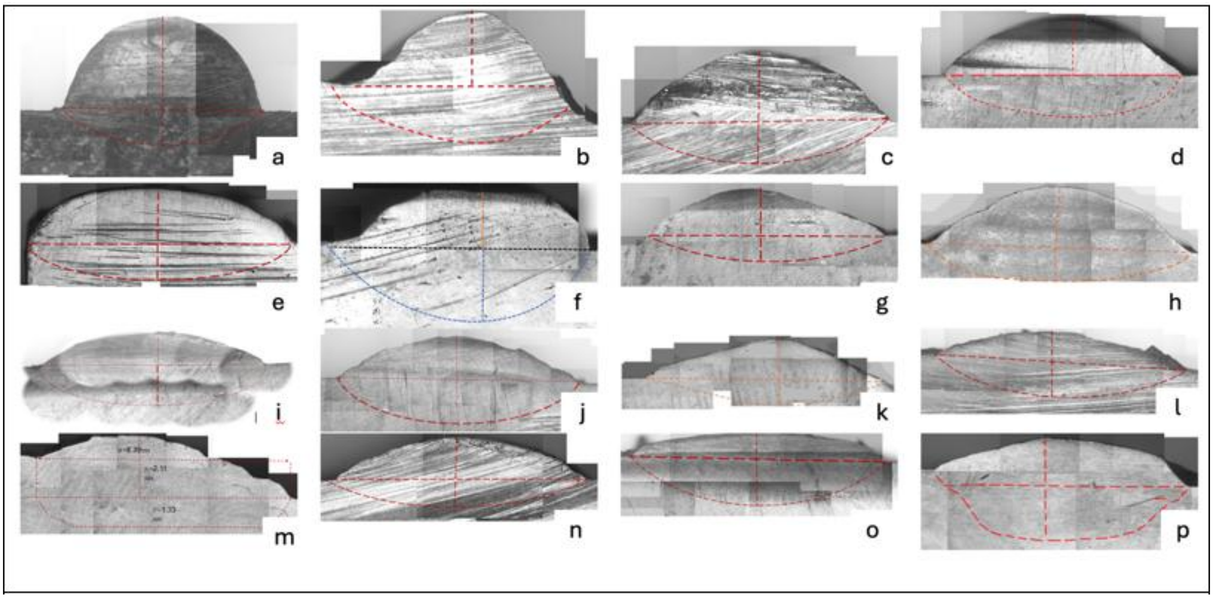

Figure 2: stitch cross sectional images of 16 weld samples parameter of each picture in table 1

The relationship between heat input and bead reinforcement height was found to be more complex, exhibiting a non-linear trend. At lower heat input levels, the reinforcement height increased with increasing heat input, as the enhanced energy deposition led to more molten material being deposited on the weld surface as shown in figure 2 and 3. However, beyond a certain threshold of heat input, the reinforcement height began to decrease, likely due to the onset of excessive melting and the resulting wider bead profile, which can compromise the structural integrity of the weld [1]. This phenomenon underscores the critical balance that must be struck between heat input and weld bead geometry, as excessive reinforcement can lead to issues such as localized overheating and compromised mechanical properties in the heat-affected zone, which has been documented in various studies focusing on the effects of welding parameters on material microstructure and hardness. Table 2 shows the process parameter and bead mesurments.

Table 2: process parameter and bead mesurment

No.	Speed	Amp	Volt	Heat input	Reinforcement	Width	Penetration
	m/min	A	V	KJ/mm	mm		
a	0.288	89	22.5	417.2	6.8	5.5	1.0
b	0.288	90	22.5	421.9	3.8	6.2	1.0
c	0.288	91	22.5	426.6	3.1	7.6	1.3
d	0.288	92	22.5	431.3	2.6	7.8	1.3
e	0.288	93	22.5	435.9	2.5	8.6	1.7
f	0.288	94	22.5	440.6	2.4	8.9	1.8
g	0.288	95	22.5	445.3	2.1	9.5	2.1
h	0.288	96	22.5	450.0	2.1	12.4	2.2
i	0.288	97	22.5	454.7	1.9	12.9	2.4
j	0.288	98	22.5	459.4	1.9	13.0	2.5
k	0.288	99	22.5	464.1	1.8	14.3	2.5
l	0.288	100	22.5	468.8	1.6	14.7	2.6
m	0.288	102	22.5	478.1	1.4	15.9	2.7
n	0.288	103	22.5	482.8	1.1	17.3	2.8
o	0.288	104	22.5	487.5	1.0	20.2	3.1
p	0.288	105	22.5	492.2	1.0	21.6	3.5

Table 2 shows the welding parameters, specifically focusing on the heat input and its effects on reinforcement, width, and penetration. The heat input values in KJ/mm. These values range from approximately 417 to 490 KJ/mm. The reinforcement height in millimeters, indicating how much the weld bead stands above the surface of the base material. The width of the weld bead in millimeters, showing how broad the weld bead is at the surface. The penetration depth in millimeters, which represents how deep the weld has penetrated into the base material.

The study also revealed a strong positive correlation between heat input and weld bead width, where higher heat input levels resulted in greater bead widths. This observation aligns with previous research demonstrating that an increase in welding current directly correlates with an increase in bead width, while also indicating that modifications in welding speed can inversely affect this relationship, thus further emphasizing the intricate balance required in managing input parameters to achieve the desired weld bead geometry. Additionally, the analysis highlighted that the bead width tended to increase as gas pressure was elevated during the welding process, reinforcing the notion that various welding parameters must be finely tuned to optimize bead geometry and achieve high-quality welds, thereby underscoring the need for a comprehensive understanding of these interdependencies.

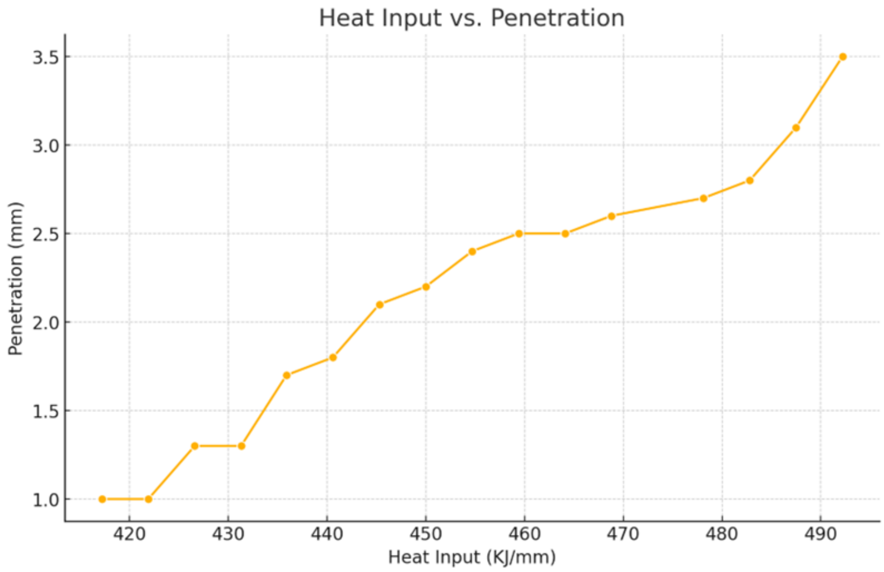

Figure 3: Effects of heat input in weld penetratioin

Figure 3 illustrates the relationship between heat input and weld penetration depth in Shielded Metal Arc Welding (SMAW). The data reveal a clear and continuous positive correlation, where increasing heat input leads to progressively deeper penetration into the base material. At lower heat input values, approximately 417 to 440 KJ/mm, the penetration increases moderately from 1.0 mm to around 2.1 mm. Beyond this range, particularly above 450 KJ/mm, the rate of penetration growth becomes more pronounced, with the maximum observed depth reaching 3.5 mm at a heat input of 492.2 KJ/mm. This behavior is consistent with welding fundamentals, where greater thermal energy facilitates more extensive fusion and deeper weld pool formation. Unlike bead reinforcement, which tends to stabilize or decline at higher heat inputs, penetration continues to increase without plateauing within the studied range. These results underscore the critical role of heat input in achieving sufficient fusion and joint strength, highlighting the importance of precise heat control in SMAW process optimization.

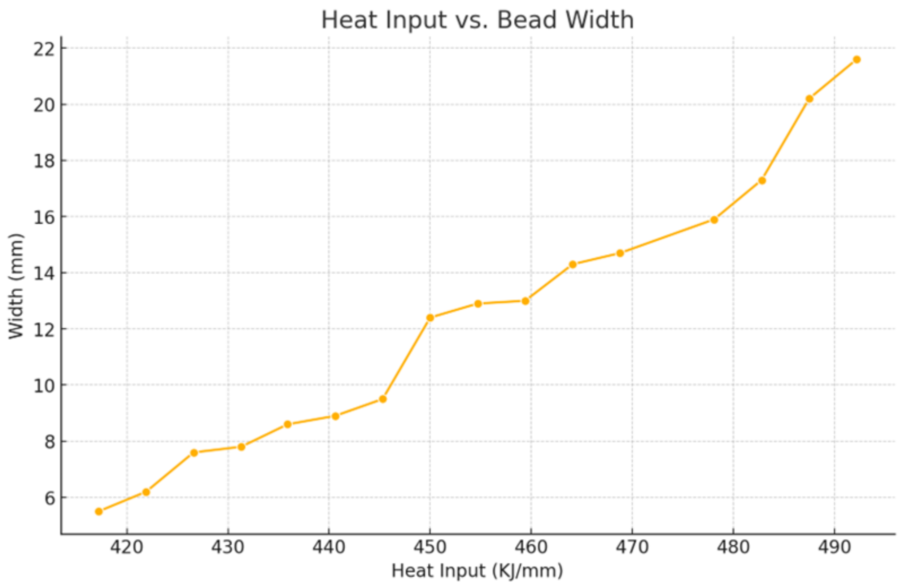

Figure 4: Effects of heat input in weld bead width

Figure 4 presents the relationship between heat input and the resulting bead width in Shielded Metal Arc Welding (SMAW). The data demonstrate a strong and consistent positive correlation, indicating that as heat input increases, the weld bead becomes progressively wider. In the lower range of heat input values (417–445 KJ/mm), the bead width shows a gradual increase from approximately 5.5 mm to 9.5 mm. A noticeable inflection occurs around 450 KJ/mm, after which the width rises more steeply, reaching a maximum of 21.6 mm at 492.2 KJ/mm. This trend reflects the increased energy density delivered to the weld pool, which enhances the melting and lateral spread of the molten metal. The steady growth in width also suggests that the weld pool becomes more fluid at higher energy levels, contributing to a broader cross-section. However, excessively wide beads can negatively affect joint quality by increasing heat-affected zone size and potential for distortion. Thus, the findings emphasize the need for precise control of heat input to ensure optimal bead geometry and structural performance in welded assemblies.

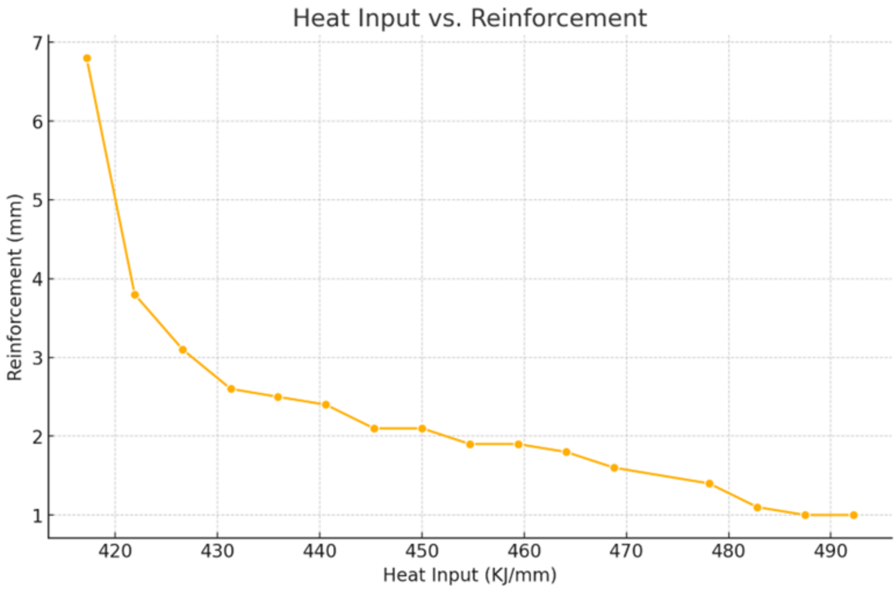

Figure 5: Effects of heat input in weld face reinforcement

Figure 5 illustrates the relationship between heat input and weld bead reinforcement height during Shielded Metal Arc Welding (SMAW). The results indicate a clear inverse correlation, wherein reinforcement decreases consistently as heat input increases. At lower heat input levels (approximately 417–430 KJ/mm), reinforcement heights range from 6.8 mm to around 2.6 mm, suggesting that reduced energy input leads to less melting and a more pronounced buildup of filler material on the weld surface. As the heat input continues to rise, reinforcement declines more gradually, ultimately stabilizing near 1.0 mm for inputs above 480 KJ/mm. This diminishing trend is likely attributable to the increased fluidity and lateral spread of the molten pool at higher energy levels, which flattens the bead profile and reduces the tendency for vertical buildup. While a certain level of reinforcement is beneficial for mechanical strength, excessive buildup can lead to stress concentrations and unnecessary post-processing. These findings underscore the importance of controlling heat input to maintain reinforcement within optimal limits, thereby improving weld quality and minimizing surface irregularities in industrial applications.

4. Conclusion

This study has provided valuable insights into the complex relationship between heat input and weld bead geometry in Shielded Metal Arc Welding processes. The findings indicate that precise adjustments to welding parameters, including heat input and travel speed, are essential for optimizing penetration depth, reinforcement height, and bead width, ultimately contributing to enhanced mechanical properties and structural performance in welded joints. Moreover, the interplay between heat input and bead geometry necessitates careful consideration of not only welding current and travel speed but also additional factors such as gas pressure and material composition, which can significantly influence the final weld characteristics and performance outcomes, as evidenced by investigations in relevant literature [1,2,4,7]. Moreover, this study reinforces the necessity for further research into optimizing these welding parameters, as previous work has demonstrated that variations in input current can significantly affect both the bead geometry and the characteristics of the heat-affected zone, thereby impacting the overall strength and durability of welded structures [3,4,7,8]. Moreover, it is imperative that future studies also consider the effects of additional variables such as ambient temperature and cooling rates, as these factors can further influence the microstructural characteristics and, ultimately, the mechanical performance of welded joints, reaffirming the critical nature of comprehensive investigations to establish robust welding protocols that ensure consistent and reliable weld quality.

Increasing heat input generally leads to a wider weld bead, while its effect on reinforcement and penetration is more complex and less pronounced. Specifically, the width of the bead shows the most significant response to increased heat input, suggesting that controlling heat input is crucial for managing bead width. Reinforcement decreases with initial increases in heat input but stabilizes, and penetration remains relatively stable throughout the range of heat inputs studied. This information can be valuable for optimizing welding parameters to achieve desired weld geometries.

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Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Authors Contributions

Abdullah Alhuzaima conceived and designed the study, supervised the experimental work, and contributed to data analysis and manuscript preparation.

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Competing Interests

The author declares no competing financial or non-financial interests.

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