

## Heat input calculation in GTAW welding to obtain values according to pWPS

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### Abstract

This study aims to determine the ideal heat input to remain within the constraints set in the preliminary Welding Procedure Specification (pWPS). Heat input greatly influences weld quality, mechanical properties, and residual stresses, yet accurate determination during Procedure Qualification Record (PQR) trials remains challenging. This research involved field data collection during PQR testing using two coupon specimens made of ASTM B564 UNS-N06625 and ASTM B444 UNS-N06625 Grade 1 materials, each with dimensions of 11.07 mm in thickness and 60.3 mm in diameter. The Gas Tungsten Arc Welding (GTAW) process was applied in the 6G position. The acceptable heat input ranges in the pWPS are: Root (1.0–2.5 kJ/mm), Hot (1.0–2.6), Filler (0.69–1.39), and Cap (0.6–1.1). In coupon test 1, two passes failed: Pass 3 (1.51) and Pass 5 (1.43). In coupon test 2, three passes exceeded limits: Pass 4 (1.64–1.97), Pass 5 (1.42–1.72), and Pass 8 (1.19). To ensure compliance, recommended heat input parameters were formulated. For the root pass, use 97–103 A, 9–10 V, over 4 min 40 sec (2.04–2.41 kJ/mm). For the hot pass, use 98–106 A, 9–10 V, for 4 min 48 sec (1.85–2.23). The filler pass should use 79–97 A, 9–10 V, for 3 min 39 sec (1.01–1.37), and the cap pass 81–90 A, 9–10 V, for 3 min 17 sec (0.64–0.79). These parameters aim to achieve high-quality welds in line with pWPS specifications.

## 1. Introduction

Welding, a technique for fusing materials using heat-induced melting, is a procedure that must comply with rigorous criteria. The welding process involves multiple steps, one of which is the Procedure Qualification Record (PQR). This is conducted to ascertain whether the Preliminary Welding Procedure Specification (pWPS) adheres to the relevant standards and specifications. This study aims to determine the ideal heat input value to remain within the constraints established in the pWPS. This study involved the collection of field data during the PQR process, which was subsequently analyzed to derive the heat input values. The PQR method was conducted with two coupon tests with ASTM B564 UNS-N06625 and ASTM B444 UNS-N06625 Grade 1 materials. The material's measurements were 11.07 mm in thickness and 60.3 mm in diameter. The method employed was Gas Tungsten Arc Welding (GTAW) in the 6G position. The heat input value limits for the pWPS are as follows: Root 1.0 – 2.5, Hot 1.0 – 2.6, Filler 0.69 – 1.39, and Cap 0.6 – 1.1. The calculation findings indicate that coupon test 1 exhibited two failed passes: maximum Pass No. 3 with a score of 1.51 and maximum Pass No. 5 with a value of 1.43. In coupon test 2, three passes were unsuccessful: Pass No. 4 with a minimum of 1.64 and a maximum of 1.97, Pass No. 5 with a minimum of 1.42 and a maximum of 1.72, and Pass No. 8 with a maximum of 1.19.

This research has conducted an assessment to ascertain the ideal heat input value in the welding process to generate high-quality welds that comply with the specifications established in the pWPS. This study outlines the suggested parameters for achieving optimal heat input: Utilize root pass with a current ranging from 97 A to 103 A and a voltage between 9 V and 10 V for 4 minutes and 40 seconds, ensuring a heat input of no less than 2.04 and no more than 2.41. Utilize

a hot pass with a current ranging from 98 A to 106 A and a voltage between 9 V and 10 V for 4 minutes and 48 seconds, ensuring a heat input of no less than 1.85 and no more than 2.23. Filler pass utilizing a current range of 79 A to 97 A and a voltage range of 9 V to 10 V for 3 minutes and 39 seconds, with a minimum heat input of 1.01 and a maximum of 1.37. Implementing a capping pass with a current range of 81 A to 90 A and a voltage range of 9 V to 10 V for 3 minutes and 17 seconds, with a minimum heat input of 0.64 and a maximum of 0.79.

## 2. Research Methods

### 2.1. PQR Record Process

In the PQR process, 2 coupon tests are prepared, each using material with specifications ASTM B564 UNS-N06625 and ASTM B444 UNS-N06625 Grade 1. The dimensions of each material are a thickness of 11.07 mm and a diameter of 60.3 mm. The welding process carried out is GTAW with a 6G position. The joint design in this PQR process uses a single-V (butt joint) with a groove angle width of 50°, a root face of 1 mm, and a root gap of 3 – 4 mm[4].

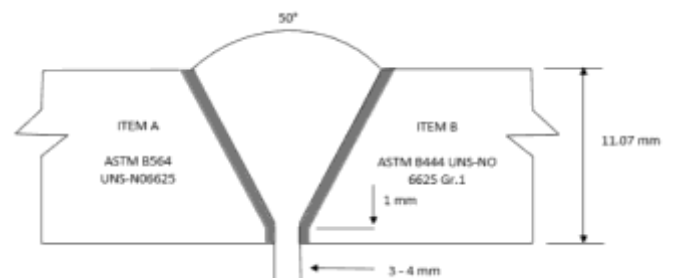


Fig. 1. Joint Design

Table 1. Material Composition

Element	Composition Limits, %	
	ASTM B564 UNS-N06625	ASTM B444 UNS- N06625 Gr.1
Carbon	0.10 max	0.10 max
Manganese	0.5 max	0.50 max
Silicon	0.5 max	0.50 max
Phosphorus	0.015 max	0.015 max
Sulfur	0.015 max	0.015 max
Chromium	20.0 min 23.0 max	20.0 min 23.0 max
Columbium + tantalum	3.15 min 4.15 max	3.15 min 4.15 max
Cobalt (if determined)	-	1.0 max
Molybdenum	8.0 min 10.0 max	8.0 min 10.0 max
Iron	5.0 max	5.0 max
Aluminum	0.4 max	0.40 max
Titanium	0.4 max	0.40 max
Nickel	58.0 max	58.0min

Table 2. Material P-Number Qualification (ASME Sec. IX Table QW/QB-422)

Spec. No	Alloy, Type, or Grade	UNS No.	Minimum Specified Tensile, ksi (MPa)	P-number	Thickness Limits, Nominal in(mm)
B/SB-564	-	N06625	120 (825)	43	≤ 4 (100)
B/SB-444	1	N06625	120 (825)	43	-

2.2. Data Collecting

During the PQR process, each test coupon is welded by a different welder. As the welder begins their task, the author immediately starts the stopwatch to time the welding process. Simultaneously, the welding current and voltage are measured with a clamp meter. These measurements, a testament to the thoroughness of our process, are recorded in the provided runsheet after each pass without fail. The welder's reference during this critical process can be found in the comprehensive parameter table, Table 3.

Table 3. Welding Parameter

Process	GTAW(Root)	GTAW(Hot)	GTAW(Filler)	GTAW(Capping)
Filler type	UTPA 6222 MO	UTPA 6222 MO	UTPA 6222 MO	UTPA 6222 MO
Supplier	Bohler	Bohler	Bohler	Bohler

Size mm	2.0	2.0	2.0	2.0
SFA N°	5.14	5.14	5.14	5.14
AWS Class.	ERNiCrMo-3	ERNiCrMo-3	ERNiCrMo-3	ERNiCrMo-3
F N°	43	43	43	43
Current	DIRECT	DIRECT	DIRECT	DIRECT
Amps	95 – 105	100 – 110	70 – 105	74 – 96
Volts	9 – 11	9 – 11	9 – 11	9 – 11
Speed				
Cm/min	2.7 – 5.1	2.8 – 5.4	5.0 – 9.0	6.0 – 9.6
Heat input				
KJ/mm	1.0 – 2.5	1.0 – 2.6	0.67 - 1.39	0.6 – 1.1
Polarity	DCEN	DCEN	DCEN	DCEN
Arc time	N.A	N. A	N.A	N.A

The number of passes produced in both coupon tests was 9, a significant finding, consisting of 1 root, 1 hot pass, 4 fillers, and 3 capping. The amount of filling is adjusted according to the thickness and diameter of the material and the bevel to be filled. The data generated from both coupon tests during the PQR process are in Tables 4 and 5, and for the welding sequence, it is in Figure 2.

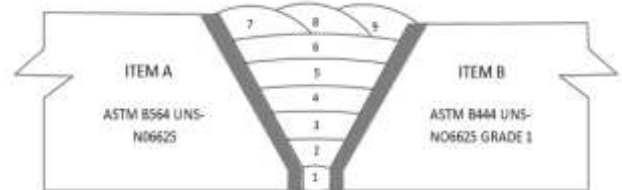


Fig. 2. Welding Sequence

Table 4. Parameter for PQR of Coupon Test 1

Pass No.	Weld Pass	Ampere		Volt		Time	
		Min	Max	Min	Max	Minute	Second
1	Root	95.8	100.2	9.2	9.5	5	15
2	Hot	95.7	103.5	9.1	9.7	5	48
3	Fill	90.6	103.8	10.2	10.8	3	28
4	Fill	95.7	103.3	9.2	9.8	3	25
5	Fill	101.2	106.2	10.8	11.8	3	36
6	Fill	83.9	98.2	9.6	10.1	3	44
7	Cap	88.9	95.6	9.5	10.0	4	1
8	Cap	80.2	92.1	10.2	10.3	4	17
9	Cap	83.9	91.9	9.9	10.5	4	8

Table 4 shows the actual parameter data on coupon test 1 during the PQR process. The root pass produces a minimum of 95.8 and a maximum of 100.2 amps, a minimum of 9.2 and a maximum of 9.5 volts. These values represent the range of acceptable performance for the root pass. The welding process time for the root pass is 5 minutes 15 seconds. The hot pass produces a minimum of 95.7 and a maximum of 103.5 volts, a minimum of 9.1 and a maximum of 9.7 volts, and a welding process time of 5 minutes 48 seconds.

The filler pass 1 produces a minimum of 90.6 and a maximum of 103.8 volts, a minimum of 10.2 and a maximum of 10.8 volts, and a welding process time of 3 minutes 28 seconds. The filler pass 2 produces a minimum of 95.7 and a maximum of 103.3 volts, a minimum of 9.2 and a maximum of 9.8 volts, and a welding process time of 3 minutes 25 seconds. In filler pass 3, it produces a minimum of 101.2 and a maximum of 106.2 amps, a minimum of 10.8 and a maximum of 11.8 volts, and a welding process time of 3 minutes 36 seconds. In filler pass 4, it produces a minimum of 83.9 and a maximum of 98.2 amps, a minimum of 9.6 and a maximum of 10.1 volts, and a welding process time of 3 minutes 44 seconds. In capping pass 1, it produces a minimum of 88.9 and a maximum of 95.6 amps, a minimum of 9.5 and a maximum of 10.0 volts, and a welding process time of 4 minutes 1 second. In capping pass 2, it produces a minimum of 80.2 and a maximum of 92.1 amps, a minimum of 10.2 and a maximum of 10.3 volts, and a welding process time of 4 minutes 17 seconds. In capping pass 3, the ampere produced was a minimum of 83.9 and a maximum of 91.9, the volts were a minimum of 9.9 and a maximum of 10.5, and the welding process took 4 minutes and 8 seconds.

Table 5. Parameter for PQR of Coupon Test 2

Pass No.	Weld Pass	Ampere		Volt		Time	
		Min	Max	Min	Max	Minute	Second
1	Root	98.6	105.3	9.2	10.5	4	5
2	Hot	100.7	107.7	10.2	11.2	3	48
3	Fill	87.9	100.4	8.6	9.7	3	15
4	Fill	100.3	107.2	10.4	11.7	4	30
5	Fill	88.7	102.4	10.2	10.7	4	58
6	Fill	75.8	95.9	10.0	11.2	3	42
7	Cap	74.8	93.8	9.4	10.4	3	41
8	Cap	90.7	100.1	10.2	11.8	3	45
9	Cap	79.2	88.4	9.3	10.1	2	25

The actual parameter data for coupon test 2 during the PQR procedure is presented in Table 5. The root pass generates a minimum current of 98.6 amps and a maximum of 105.3 amps, with a voltage range of 9.2 to 10.5 volts and a total welding duration of 4 minutes and 5 seconds. The hot pass yields a minimum voltage of 100.7 volts and a maximum of 107.7 volts, with a minimum of 10.2 volts and a maximum of 11.2 volts, and a welding process duration of 3 minutes and 48 seconds. The filler passes 1 yields a voltage range of 87.9 to 100.4 volts, a secondary voltage range of 8.6 to 9.7 volts, and a total welding process duration of 3 minutes and 15 seconds. The filler passes two yields a minimum voltage of

100.3 volts and a maximum of 107.2 volts, with a minimum of 10.4 volts and a maximum of 11.7 volts, and a welding process duration of 4 minutes and 30 seconds. Filler pass 3 yields a minimum current of 88.7 amps and a maximum of 102.4 amps, with a minimum voltage of 10.2 volts and a maximum of 10.7 volts, resulting in a welding process duration of 4 minutes and 58 seconds. Filler pass 4 yields a minimum current of 75.8 amps and a maximum of 95.9 amps, with a minimum voltage of 10.0 volts and a maximum of 11.2 volts, and a total welding process duration of 3 minutes and 42 seconds.

During capping pass 1, the process yields a minimum current of 74.8 amps and a maximum of 93.8 amps, with a minimum voltage of 9.4 volts and a maximum of 10.4 volts, resulting in a total welding duration of 3 minutes and 41 seconds. During capping pass 2, the process yields a minimum current of 90.7 amps and a maximum of 100.1 amps, with a minimum voltage of 10.2 volts and a maximum of 11.8 volts, and a total welding duration of 3 minutes and 45 seconds. During capping pass 3, the amperage ranged from a minimum of 79.2 to a maximum of 88.2, while the voltage varied from a minimum of 9.3 to a maximum of 10.1. The duration of the welding process was 2 minutes and 25 seconds.

### 3. Results and Discussion.

Based on the data taken, a travel speed calculation will be carried out using the travel speed formula to obtain the welding movement speed value (Eq. 1).

$$\text{Travel Speed} = (\text{Weld Length}) / (\text{Weld Time}) \quad (1)$$

From the calculation results, the travel speed value is obtained in the following table.

Table 6. Results of Travel Speed

Pass No.	Weld pass	Travel Speed (mm/min)	
		Coupon test 1	Coupon test 2
1	Root	23	29
2	Hot	24	36
3	Fill	45	48
4	Fill	50	38
5	Fill	53	38
6	Fill	55	56
7	Cap	56	61
8	Cap	52	60
9	Cap	54	51

Table 6 shows the results of travel speed calculations, where the root pass on coupon test 1 has a value of 23 mm/min and coupon test 2 has a value of 29 mm/min. Hot pass on coupon test 1 has a value of 24 mm/min, and coupon test 2 has a value of 36 mm/min. Filler passes 1 on coupon test 1 has a value of 45 mm/min, and coupon test 2 has a value of 48 mm/min. Filler passes two on coupon test 1, which has a value of 50 mm/min, and coupon test 2, which has a value of 38 mm/min. Filler passes three on coupon test 1, which has a value of 53 mm/min, and coupon test 2, which has a value of 38 mm/min. Filler passes four on coupon test 1, which has a value of 55 mm/min, and coupon test 2, which has a value of 56 mm/min. Capping pass one on coupon test 1 has a value

of 56 mm/min, and coupon test 2 has a value of 61 mm/min. Capping passes two on coupon test 1 with a value of 52 mm/min and coupon test 2 with a value of 60 mm/min. Capping passes three on coupon test 1 with a value of 54 mm/min and coupon test 2 with a value of 51 mm/min. The heat input calculation is carried out using the data in Tables 4 and 5 and the travel speed data in Table 6 using the heat input formula (Eq. 2).

$$Q = \frac{U \cdot I \cdot 0,06}{V} \quad (2)$$

Where :

$Q$  : heat input (Kj/mm)

$U$  : ampere (A)

$I$  : volt (V)

$V$  : travel speed (mm/min)

Table 7. Results of Heat Input

Pass No.	Weld Pass	Heat input (Kj/min)			
		Coupon test 1		Coupon test 2	
		Min	Max	Min	Max
1	Root	2.32	2.50	1.85	2.26
2	Hot	2.21	2.55	1.71	2.00
3	Fill	1.24	1.51	0.95	1.23
4	Fill	1.04	1.21	1.64	1.97
5	Fill	1.25	1.43	1.42	1.72
6	Fill	0.87	1.07	0.81	1.15
7	Cap	0.91	1.03	0.69	0.96
8	Cap	0.94	1.09	0.93	1.19
9	Cap	0.92	1.07	0.87	1.06

The resulting heat input value is obtained from the calculation results in the following table 7 shows the calculation results of the heat input that has been obtained in the root pass section for coupon test 1 with a minimum value of 2.32 Kj/min and a maximum of 2.50 Kj/min, for coupon test 2 with a minimum value of 1.85 Kj/min and a maximum of 2.26 Kj/min. In the hot pass section for coupon test 1, with a minimum value of 2.21 Kj/min and a maximum of 2.55 Kj/min, for coupon test 2, with a minimum value of 1.71 Kj/min and a maximum of 2.00 Kj/min. In the filler pass 1 section for coupon test 1 with a minimum value of 1.24 Kj/min and a maximum of 1.51 Kj/min, for coupon test 2 with a minimum value of 0.95 Kj/min and a maximum of 1.23 Kj/min. In the filler pass 2 section for coupon test 1 with a minimum value of 1.04 Kj/min and a maximum of 1.21 Kj/min, for coupon test 2 with a minimum value of 1.64 Kj/min and a maximum of 1.97 Kj/min. In the filler pass 3 section for coupon test 1 with a minimum value of 1.25 Kj/min and a maximum of 1.43 Kj/min, for coupon test 2 with a minimum value of 1.42 Kj/min and a maximum of 1.72 Kj/min. In the filler pass 4 section for coupon test 1 with a minimum value of 0.87 Kj/min and a maximum of 1.07 Kj/min, for coupon test 2 with a minimum value of 0.81 Kj/min and a maximum of 1.15 Kj/min.

In the capping pass 1 section for coupon test 1 with a minimum value of 0.91 Kj/min and a maximum of 1.03 Kj/min, for coupon test 2 with a minimum value of 0.69 Kj/min and a maximum of 0.96 Kj/min. In the capping pass 2 section for coupon test 1 with a minimum value of 0.94 Kj/min and a maximum of 1.08 Kj/min, for coupon test 2 with a minimum value of 0.93 Kj/min and a maximum of 1.19 Kj/min. In the capping pass 3 section for coupon test 1 with a

minimum value of 0.92 Kj/min and a maximum of 1.07 Kj/min, for coupon test 2 with a minimum value of 0.87 Kj/min and a maximum of 1.06 Kj/min.

Table 8. Results of Evaluation

Pass No.	Weld Pass	Heat input (Kj/min)				Evaluation
		Coupon test 1		Coupon test 2		
		Min	Max	Min	Max	
1	Root	2.32	2.50	1.85	2.26	YES
2	Hot	2.21	2.55	1.71	2.00	YES
3	Fill	1.24	1.51	0.95	1.23	YES
4	Fill	1.04	1.21	1.64	1.97	NO
5	Fill	1.25	1.43	1.42	1.72	NO
6	Fill	0.87	1.07	0.81	1.15	YES
7	Cap	0.91	1.03	0.69	0.96	YES
8	Cap	0.94	1.08	0.93	1.19	NO
9	Cap	0.92	1.07	0.87	1.06	YES

The computations conducted on coupon test 1 and coupon test 2 yield the results presented in Table 8. The limit settings on the pWPS reference are as follows: Root 1.0 - 2.5, Hot 1.0 - 2.6, Filler 0.69 - 1.39, and Cap 0.6 - 1.1. In coupon test 1, multiple failed pass results were identified; specifically, maximum Pass No. 3 in the Weld Pass Filler section recorded a value of 1.51 Kj/min due to the duration of the welding process, while maximum Pass No. 5 in the same section yielded a value of 1.43 Kj/min as a result of exceeding the reference limits for amperage and voltage. The outcomes of both passes surpassed the reference thresholds since the maximum welding parameters in the filler portion were 1.39 kJ/min. The heat input for coupon test 2 in the failed pass is at the minimum and maximum of Pass No. 4 in the Weld Pass Filler section, with a minimum value of 1.64 kJ/min and a maximum of 1.97 kJ/min due to the amperage and voltage exceeding the reference limit. Pass No. 5 of the Weld Pass Filler section has a failure at both the minimum and maximum, with a minimum value of 1.42 Kj/min and a maximum of 1.72 Kj/min, attributed to the duration of the welding process.

Both passes' values surpass the minimum and maximum reference limits for the welding parameters of the filler section, which are 0.69 Kj/min and 1.39 Kj/min, respectively. Subsequently, in the identical coupon test, another unsuccessful outcome occurred at the maximum of Pass No. 8 in the Weld Pass Capping section, registering a value of 1.19 Kj/min due to the amperage and voltage over the reference threshold. The pass results surpass the reference threshold, as the maximum welding parameters in the capping portion are 1.1 Kj/min. The data indicates that in coupon test 1, there were two unsuccessful passes in the filler pass portion: Pass No. 3 and Pass No. 5. In coupon test 2, there were three unsuccessful passes in Pass No. 4 and 5 filler pass sections and Pass No. 8 capping pass section. In the root pass of pass no. 1, both coupon tests 1 and 2 were allowed; however, in the filler pass region of pass no. 3-5, the average results were failures. During the 4-hour welding process from initiation to capping, it is of utmost importance to maintain a high level of vigilance to prevent potential heat input errors during the fill pass, thereby ensuring the quality of the weld.

#### 4. Conclusions.

The test results found that in coupon test 1, there were two failed passes in Pass No. 3 and Pass No. 5 filler sections. In coupon test 2, there were three failed passes in Pass No. 4 and 5 filler sections and Pass No. 8 capping section. Factors that influence the occurrence of heat input discrepancies include the duration of welding and the high and low amperages and voltages during the welding process. From the study's results, heat input calculations were carried out to ensure that the resulting values were within the pWPS reference limits. The recommended parameters for obtaining optimal heat input in this study are in the root pass with a minimum ampere of 97 A and a maximum of 103 A, volts with a minimum of 9 V and a maximum of 10 V in 4 minutes 40 seconds to obtain a heat input with a minimum of 2.04 and a maximum of 2.41 which does not exceed the pWPS limit. In the hot pass with a minimum ampere of 98 A and a maximum of 106 A, volts with a minimum of 9 V and a maximum of 10 in 4 minutes 48 seconds so that it gets a heat input with a minimum of 1.85 and a maximum of 2.23 which does not exceed the pWPS limit. In the filler pass with a minimum ampere of 79 A and a maximum of 97 A, volts with a minimum of 9 V and a maximum of 10 V in 3 minutes 39 seconds so that it gets a heat input with a minimum of 1.01 and a maximum of 1.37 which does not exceed the pWPS limit. In the capping pass with a minimum ampere of 81 A and a maximum of 90 A, volts with a minimum of 9 V and a maximum of 10 V in a period of 3 minutes 17 seconds so that it gets a heat input with a minimum of 0.64 and a maximum of 0.79 which does not exceed the pWPS limit.

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