KEY-HOLE PLASMA ARC WELDING OF 8 MM THICK MARAGING STEEL – A COMPARISON WITH MULTI-PASS GTAW

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ABSTRACT

Maraging steel is an iron nickel alloy with typical 18Ni-8Co-5Mo composition. It has low C martensitic structure which is strengthened by precipitation of inter-metallic compounds through ageing. Due to good fracture toughness in addition to high strength to weight ratio, the steel is widely used in aerospace applications. Conventionally we have been welding 8 mm-thick maraging steel with multi-pass automatic GTAW process. The steel shows "austenite reversion" phenomenon when heated to two phase (austenite + ferrite) region. Due to this phenomenon, maraging steel weld has two peculiar heat-affected zones; zone A nearest to the weld which is heated to fully austenitic region and zone B adjacent to it is heated to two phase region. Zone B contains reverted austenite which is not hardened by ageing. In conventional GTAW weld, zone B is quite wide, due to cumulative effect of multipasses. As zone B is not hardened fully by aging, it affects the mechanical properties of weldments. To reduce the width of the HAZ (zone B), single pass key-hole Plasma Arc Welding (PAW) was evaluated for 8 mm-thick plate. This paper describes the effect of weld passes and heat input on weld properties as a comparative study of single pass PAW and multi-pass GTAW. Mechanical properties (hardness, tensile properties, and fracture toughness) and macroscopic observations have been discussed. Also filler wire consumption & arcing time has being compared which are important aspects for production. The effect of single pass from multi-pass is very much visible in macroscopic observations. PAW weld shows significant reduction in width of HAZ (zone B) as compared to multi-pass GTAW. In aged condition in PAW weld does not show sudden drop in hardness in HAZ which is a common phenomenal in GTAW & the Improvement has been observed in tensile properties of PAW weld.

IIW-Thesaurus keywords: Maraging steels; Plasma arc welding; Heat affected zone; Ageing.

1 Introduction

Maraging steels are class of high strength steels characterized by very low carbon content and the use of substantial elements to produce age hardening in Iron-Nickel martensite. The term maraging was coined from a combination of martensite and ageing [1]. The addition of 18 % nickel to a low-carbon steel ensures the formation of a soft martensite (~30 HRC) on cooling from the austenitising temperature. On subsequent ageing at a temperature below 500 °C, several intermetallic phases precipitate in the soft martensite matrix. Considerable hardening occurs during the ageing of martensite and a tensile strength of the order of 1 800 MPa and higher is usually achieved.

Welding of maraging steels is usually carried out in solution annealed condition by conventional multi-pass GTAW process which helps in attaining good fracture toughness with clean weld. Strength is further achieved by subsequent ageing treatment.

The compositions of filler material used to join maraging steel are often similar to that of the base material. Also, the cooling rate in all welding processes is relatively high, much higher than in air cooling, thus producing a quenching effect. Consequently, the structure of weld metal in the as-welded condition resembles that of solution – treated base material. Subsequent ageing induces precipitation of intermetallic compound, causing hardening.

The reactions in the HAZ in welded maraging steel are slightly more complex than in the fusion zone. Three regions are usually identified in the HAZ. Nearest to the weld, is a zone A, that is heated into the fully austenitic region, (say peak temperatures > 750 °C) during welding, and transforms to martensite on cooling. Next to this, is a narrow band (zone B), that is heated into the two – phase austenite-ferrite field (say peak temperatures from 600 °C to 750 °C) during welding. Finally, there is a zone C outside that experiences peak temperature much lower than the above.

In zone A, the as-welded microstructure is similar to that of solution – treated maraging steel, i.e., a low – carbon Fe-Ni martensite with an approximate hardness of 350 VHN. There could be slight reduction in strength in the course grain region, nearest to the fusion boundary, on account of high peak temperature > 730 °C during welding and the

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consequent large prior-austenite grain size. When the joint is aged after welding, the strength of this zone increases to that of age – hardened maraging steel.

In zone B, on the other hand, the base material is heated into the austenite + ferrite field and partial conversion to reverted austenite occurs. Because of its composition, this austenite is stable on cooling and does not harden during post-weld heat treatment. Zone B thus remains weaker than the rest of the HAZ. It is often termed as 'the eye - brow region' or 'dark band' because it etches black [2].

The strength reduction due to zone B is greater if its width increases. This can occur with high heat input and it has been shown by Peterson using Gleeble-simulated HAZ specimens that high heat input decreases the strength of HAZ. Low that heat input and a thinner band in zone B is also beneficial because the weak zone is then supported by stronger surrounding material. The toughness of HAZ, however, has been shown to undergo no reduction from that of the unwelded plate. In maraging steels, it is not possible to attain 100 % weld efficiency due to many metallurgical changes occurs in heat-affected zones while welding which are mainly governed by heat input and number of weld passes. In this study, Keyhole Plasma Arc Welding (PAW) process has been evaluated to weld 8 mm-thick maraging steel (M 250) plates in single pass and properties are compared with multi-pass GTAW.

Key-Hole Plasma Arc Welding (PAW) VS Gas Tungsten Arc Welding (GTAW)

Figure 1 shows the schematic diagrams of a) Gas Tungsten Arc Zone and b) Plasma Arc Zone [3]. It was observed that the plasma arc is more constricted compare to gas tungsten arc. It was also observed that the high energy density process gives fast cooling rate. F.H. Lang and N. Kenyon investigated the effect of fast cooling rate and they suggested that fast cooling rate is beneficial for M 250 maraging steel properties [4].

For higher thickness (> 3 mm), to utilize the high temperature part of plasma arc, on account for welding of its high kinetic energy, requires the application of welding of a special technique, known as the "keyhole effect". The straight edges of plate to be joined are butted together, heated by plasma jet, and the force of the arc produces a hole through the thickness and this is traversed along the joint. Surface tension causes the liquid metal to flow together behind the advancing arc and so form the weld bead [5]. Transferred arc is used for key-hole PAW.

2 Experimental work

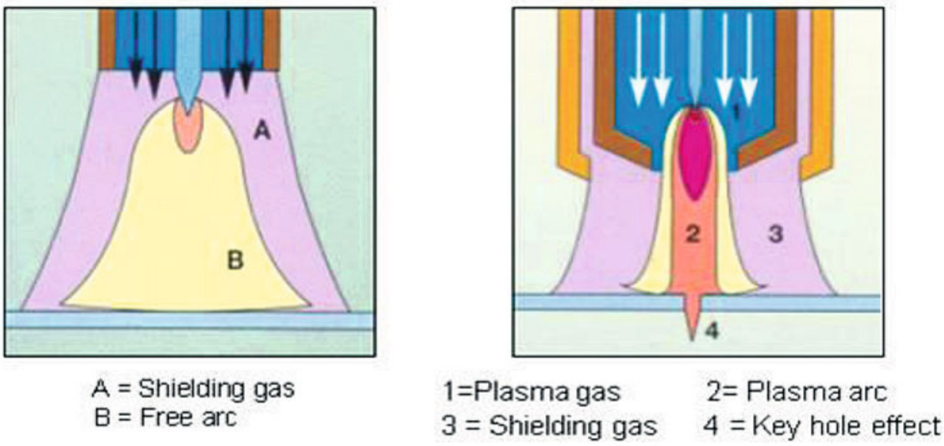
All experiments were performed on solution annealed 8 mm thickness M 250 coupons. Table 1 shows the chemical composition of the plates. Filler wire MDN 250 W2 type of 1.6 mm diameter has been used for welding. Table 2 shows the chemical composition of filler wire. 10 coupons (size = 150 mm, width X = 500 mm, length X = 8 mm) were welded by each process that is with machine GTAW and with PAW process. For machine GTAW, single V groove was used, and, for PAW, square butt zero gap joint was used for welding. (See Figure 2)

All the coupons after welding and NDE were heat treated for ageing at 485 °C for 3 h and 15 min.

The M 250 weldments, welded by GTAW & Keyhole PAW are characterized by Non-Destructive Examinations (visual, liquid penetrant, X-ray radiographic & ultrasonic examinations) after welding. Ultrasonic testing was done with angle beam scan by using 45°, 60°, 70 probe angles. AMS G notch was used as standard reference reflector. UT was also done with normal beam scanning by using 2 mm diameter FBH as standard reference reflector.

The weldments including HAZ have been examined for macro & microscopic examination.

The mechanical properties evaluated were micro hardness, Transverse tensile & Plain strain fracture toughness. Transverse tensile test was done as per ASTM A-370 [6] for determination of the tensile stress and 0.2 % proof



a) Gas Tungsten Arc Zone

b) Plasma Arc Zone

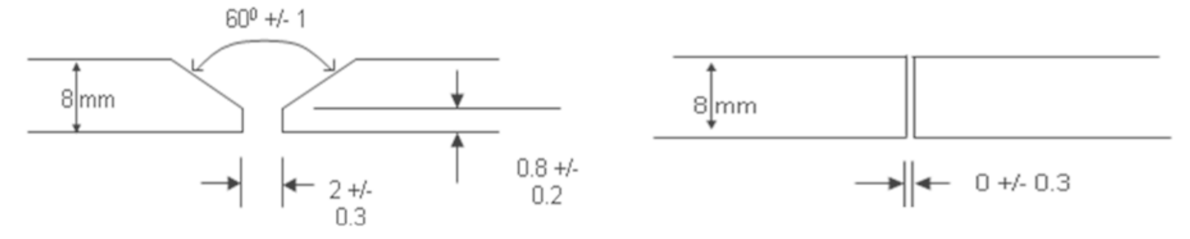
Figure 1 – Schematic diagrams of GTAW & PAW arc zones

Table 1 – Chemical composition of M 250 base metal

C	Mn	Si	S	P	Ni	Mo	Co	Ti	Al	Fe	O_2	N_2	H_2
0.0041	0.02	0.02	0.003	0.004	18.18	4.80	8.06	0.44	0.11	Bal.	5	1	11

Table 2 – Data representing the chemical composition of MDN 250 W2 type filler wire

C	Mn	Si	S	P	Ni	Mo	Co	Ti	Al	Fe	O_2	N_2	H_2
0.005	0.02	0.01	0.006	0.004	18.04	2.6	11.69	0.17	0.4	Bal	34	2	15



a) Gas Tungsten Arc WEP

b) Plasma Arc WEP

Figure 2 – Schematic diagrams of GTAW & PAW Weld Edge Preparation (WEP)

stress. Plain strain fracture toughness test was measured as per ASTM E-399 [7] to determine the plain strain fracture toughness (K_{1C}) by fatigue crack in compact specimen.

3 Results and discussions

3.1 Welding parameters

Table 3 shows comparison of process parameters and heat input between the GTAW and PAW process. It was observed that, in PAW process, the heat input was 2.55 kJ/mm in single pass, whereas, in GTAW process during first pass (Root pass), the heat input was 1.69 kJ/mm, and, in the second and third pass, it was 1.44 kJ/mm each and in the fourth pass 1.88 kJ/mm. Thus, GTAW process gives repetitive heat input to the plate, which affects mechanical and metallurgical properties of the weld.

3.2 Non-Destructive Examination (NDE)

After welding the M 250 weldments, welded by GTAW & Keyhole PAW are examined by Non-Destructive testing (visual, liquid penetrant, radiographic & ultrasonic examinations).

Visual examination of all the coupons was carried out in as welded condition prior to grinding and other NDE. Coupons were found satisfactory with respect to root penetration and weld bead finish profile.

Liquid penetrant examination was carried out on both sides of the surfaces. No indications were observed.

In X-ray radiography, GTAW and PAW welds met the requirements of 1.2 mm diameter maximum size of porosity. No inclusion, Lack of fusion, lack of penetration or any other defect was observed.

In Ultrasonic testing with angle beam scanning, GTAW & PAW welds were found satisfactory with respect to requirement of less than 25 % discontinuity. Also it met the requirement of less than 100 % discontinuity in normal beam scanning.

3.3 Filler metal consumption and arcing time

Table 4 shows the data for filler metal consumption during GTAW and PAW process. In GTAW process, having 'V' groove between the plates 407 g/m of filler metal is required during the fourth pass welding. In case of PAW process, having 'square butt' edge preparation between

Table 3 – Parameters and heat input comparison between GTAW & PAW process for welding of 8 mm thick M 250 plates

Nº.	Parameters	GTAW			PAW
		1st pass	2nd and 3rd passes	4th pass	Single pass
1	Current [A]	220	210	230	280-290
2	Voltage [V]	8-10	10-12	12-13	22.4-22.8
3	Travel speed [mm/min]	78-82	105-110	95-100	155
4	Heat input per pass [KJ/mm]	1.69	1.44	1.88	2.55

Table 4 – Filler metal consumption and arcing time comparison in PAW and GTAW process for welding of 8 mm-thick M 250 plates

Description	GTAW			PAW
	1st Pass	2nd and 3rd Pass	4th Pass	Single Pass
Wire feed rate [mm/min]	610-630	620-640	620-640	700-800
Total filler metal consumption per meter length of weld [g/m]	407			72
Arcing time / meter length of weld	31.3 min			6.4 min

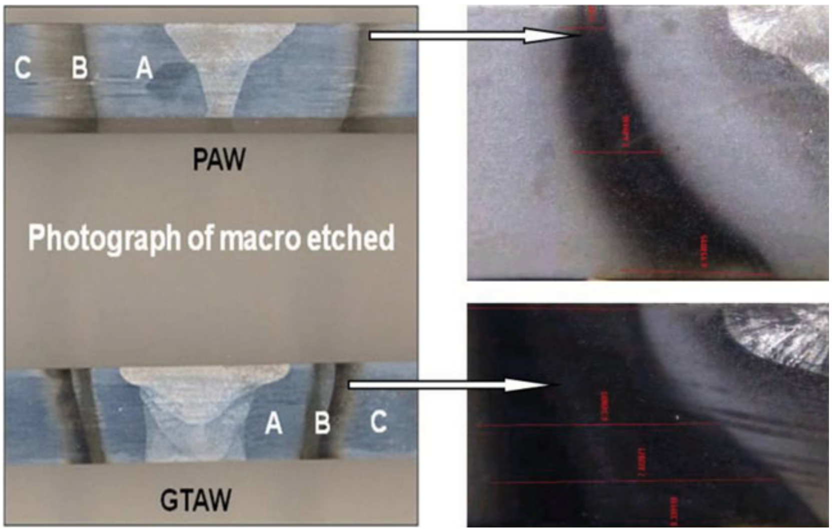


Figure 3 – Macro-photographs of PAW and GTAW weldments

the plates required only 72 g/m of filler metal during single pass welding. Arcing time to complete one meter of weld length with PAW is 1/5th of the GTAW.

3.4 Macro-examination

The width of the dark etched band (zone B defined as eyebrow zone) was measured by the image measurement software. It was observed that the width of eyebrow region in PAW weld is much less than GTAW weld. In PAW, it is about 1.5–2 mm at face side and 4-5 mm at root side while, in GTAW, it is 4-5 mm at face side and 8-9 mm at root side. (See Figure 3)

GTAW weld undergoes multiple heating and cooling cycles causing more exposure to two phase region for longer duration. F.H. Lang and N. Kenyon investigated the effect of repeated cycling of Welding on maraging steels and it was observed that the repeated cycling of heat input causes further loss in strength. This is to be expected due to more austenite formation with each cycle. There is also evidence that the reverted austenite forms more readily when there is already some austenite in the structure [3].

The reduction in width of zone B of HAZ with no significant drop in hardness after ageing in this zone explains the improvement in mechanical properties of single pass PAW weld in comparison to multi-pass GTAW weld.

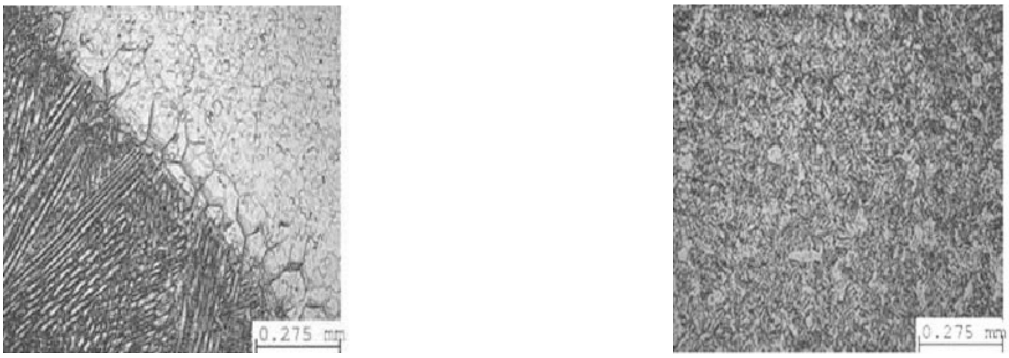
3.5 Microstructure observation [8]

3.5.1 Weld and HAZ (As-welded) by PAW process

Figures 4 a) and b) show the microstructures of the PAW weld and HAZ in as welded condition respectively. In Figure 4 a) the weld, fusion line and HAZ-A of the weldment was observed and it was found that in this region the epitaxial grain growth was present. The phases in the weld region were martensite and reverted austenite. In Figure 4 b) the reverted austenite was present. In the microphotographs martensite appeared black and the reverted austenite as white dispersion [4].

3.5.2 Weld and HAZ (After ageing) by PAW process

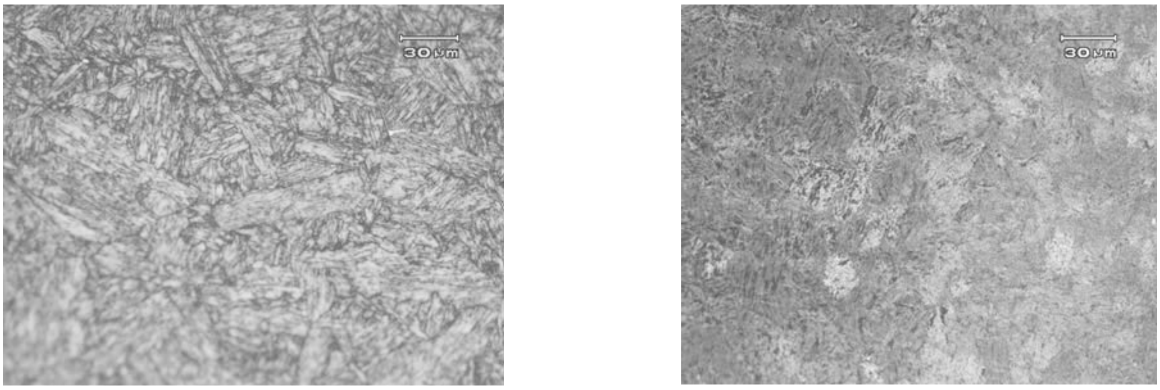
Figures 5 a) and b) show the microstructures of the PAW weld and HAZ in ageing condition respectively. Even after ageing, the reverted austenite was present, which indicate that during ageing, the austenite was not converted to Martensite [4]. It was observed that, in PAW weld and HAZ-B (Eyebrow) region, the reverted austenite is present as like GTAW weld. There is no significant difference in microstructures in weld and HAZ produced by PAW and GTAW process.



a)
Magnification: 100 X
Area: Weld, fusion line and HAZ-A
Observation: Dendrite growth and columnar structure

b)
Magnification: 200 X
Area: HAZ-B
Observation: Martensite with fine dispersion of stable reverted austenite

Figure 4 – Microphotographs of PAW M 250 weld showing a) weld, fusion line and HAZ-A and b) HAZ-B in as welded condition



a)
Magnification: 500 X
Area: Weld
Observation: Martensite with fine dispersion of stable reverted austenite

b)
Magnification: 200 X
Area: HAZ-B
Observation: Martensite with fine dispersion of stable reverted austenite

Figure 5 – Microphotographs of PAW M 250 weld showing a) weld and b) HAZ-A and HAZ-B aged condition

3.6 Mechanical properties

3.6.1 Microhardness

Figures 6 and 7 show microhardness graph in as weld condition and after ageing of PAW & GTAW welds (starting from weld centre towards base metal including all three HAZ). It is observed that in as weld condition, the hardness in HAZ-B (Eye brow region) increases near to the value of hardness observed in aged condition. The increase is more in GTAW. This is due to temperature rise in HAZ-B region (approximately 450-525 °C) during welding, which is as high as the temperature required for ageing. Microhardness of PAW HAZ (zone B) PAW does not show any significant reduction in hardness in zone B as observed in GTAW which indicates less presence of soft austenite phase in PAW HAZ.

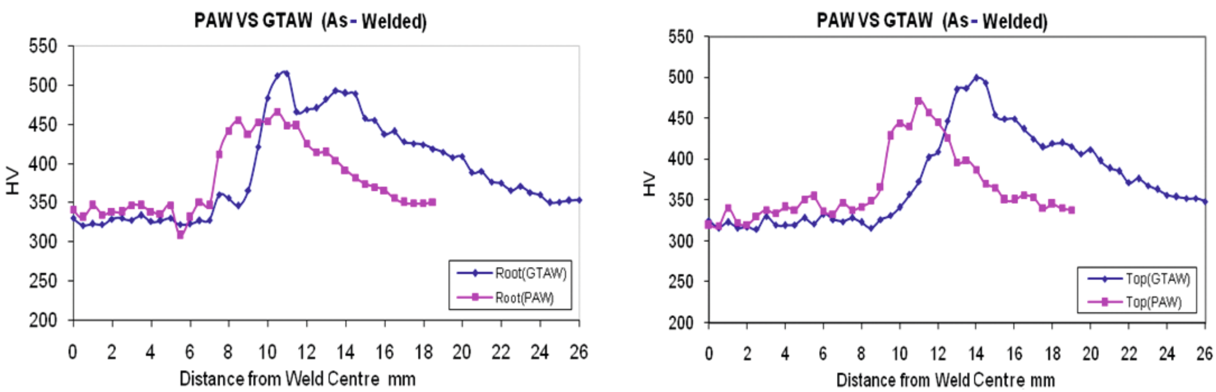


Figure 6 – Microhardness graphs of PAW and GTAW weldments (as-welded condition)

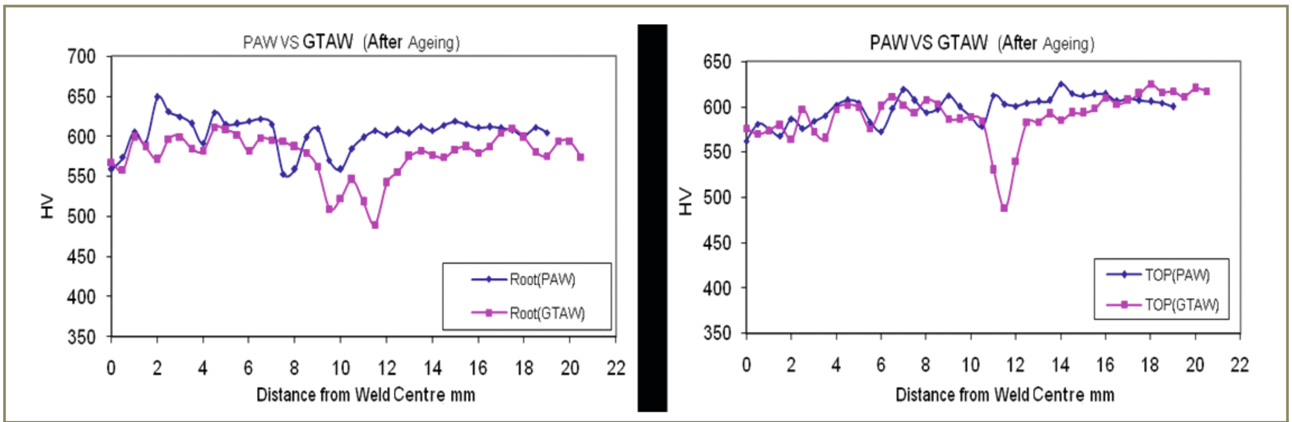


Figure 7 – Microhardness graphs of PAW and GTAW weldments (after ageing)

3.6.2 Tensile properties

Test coupons were examined for transverse tensile after ageing heat treatment. Tables 5 and 6 show the results of tensile properties (UTS, 0.2 % YS and % E) of PAW weld and GTAW weld coupons respectively.

PAW weld shows about 3 to 4 % improvement in UTS and 0.2 % YS as shown in Table 7.

3.6.3 Fracture Toughness Properties

Plane strain fracture toughness properties were evaluated after ageing treatment. Tables 5 and 6 show the results of fracture toughness properties (K1C) of PAW weld and GTAW weld coupons respectively.

The PAW K_{1C} values are comparable to GTAW weld as shown in Table 7.

4 Conclusions

1. 8 mm-thick M 250 plates were welded in single pass by Keyhole Plasma Arc Welding (PAW) successfully.
2. The PAW process can tolerate the root gap up to 0.6 mm and off set up to 0.4 mm with increasing the wire feed.
3. In PAW process, filler metal consumption is very less important due to square butt edge preparation and joint filling in single pass. The filler metal consumption is 1/5 of the Gas Tungsten Arc Welding (GTAW) process.
4. The mechanical properties i.e. 0.2 % proof stress and transverse tensile strength of M 250 weld produced by PAW process shows about 3-4 % improvement from GTAW process. However fracture toughness is comparable to that of GTAW welds.

Table 5 – Mechanical properties of PAW weld from 10 coupons

ID. No	Transverse tensile			FTT	ID. No	Transverse tensile			FTT
	0.2 % YS [MPa]	UTS [MPa)	% E	K_{1C} [MPa√M]		0.2% YS [MPa]	UTS [MPa]	% E	K_{1C} [MPa√M]
	1790	**1848**	5.58	79.32		1728	1773	5.2	80.07
01	1731	1783	4.88	80.94	06	1745	1786	5.6	80.08
	1722	1756	4.84	81.68		1746	1782	6.6	83.36
	1699	1756	5.72	79.18		1723	1773	6.8	82.18
02	1716	1775	5.08	79.3	07	1716	1767	5.9	79.82
	1725	1766	5.16	80.29		1710	1771	6.1	85.1
	1739	1786	3.32	81.64		1759	1793	5.9	79.72
03	1754	1794	5.78	83.9	08	1766	1800	6.2	82.42
	1741	1784	2.84	88.46		1740	1784	6.3	82.29
	1699	**1739**	4.16	80.18		1699	1754	8.4	81.31
04	1716	1765	7.52	83.45	09	1710	1765	8.9	**88.55**
	1711	1770	6.86	80.92		1709	1764	9.2	83.27
	1708	1748	5.56	79.09		1707	1746	4.9	79.24
05	1705	1753	5.92	**78.96**	10	1699	1747	4.2	81.27
	1688	1735	5.72	83.03		1738	1767	5.7	79.13

Table 6 – Mechanical properties of GTAW weld from 10 coupons

ID. No	0.2 % YS [MPa]	UTS [MPa]	K_{1C} [MPa√M]	ID. NO.	0.2 % YS [MPa]	UTS [MPa]	K_{1C} [MPa√M]
140 LS	1715	1669	80.29	150 LS	1702	1723	78.24
140 LF	1699	1661	78.38	150 LF	1805	1838	**76.17**
141 LS	1571	1653	81.86	151 LS	1619	1681	78.82
141 LF	1580	1649	85.79	151 LF	1615	1682	77.24
142 LS	1599	1638	84.77	152 LS	1681	1706	77.59
142 LF	1598	**1619**	81.27	152 LF	**1734**	1738	77.87
143 LS	1658	1716	80.25	153 LS	1623	1707	79.19
143 LF	1680	1741	76.74	153 LF	1604	1678	77.67
144 LS	1702	1723	78.49	154 LS	1708	**1805**	79.14
144 LF	1715	1756	**88.45**	154 LF	**1556**	1634	77.61

Table 7 – Comparison of mechanical properties of GTAW & PAW weldments

Properties	Base metal (Average)	GTAW weld (Average)	GTAW Weld efficiency	PAW Weld (Average]	PAW Weld efficiency
0.2 % P.S. [MPa]	1801-1843 (1822)	1658	91 %	1720	94 %
UTS [MPa]	1829-1878 (1853)	1701	92 %	1771	95 %
K_{1C} [MPa √m]	101-111 (106)	79.79	75 %	81.60	77 %

5. In aged condition, PAW weld does not show any significant reduction in hardness in HAZ-B (Eyebrow) region which is generally observed in GTAW weld.
6. The macrostructure reveals that the width of HAZ-B (Eyebrow) region in PAW weld at root is in the range of 4-5 mm where as in GTAW it is 8-9 mm due to cumulative effect of multi-passes. The HAZ-B region contains the reverted austenite and it has detrimental effect on mechanical properties.

Thus, it can be concluded that the single pass Keyhole PAW process applied to weld M 250 (Maraging steel) plates gives improved mechanical & metallurgical properties in comparison to multi-pass GTAW process. Additionally the PAW process reduces the filler wire consumption and arcing time to one-fifth of GTAW.

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