A Study on the Welding and Heat Treatment of 0.3%C-Cr-Mov Steel

K. Radhakrishnan and V. Muralidharan

Abstract 15CDV6 steel is a high-strength low-alloy steel widely used in aerospace applications to make pressure vessels, components, and structures. This steel has good fabricability and attains strength by simple heat treatment process of hardening and tempering. The unique property of this steel is, it can be welded in annealed and hardened and tempered conditions. This material has a ultimate tensile strength of minimum 980 MPa. The 0.3%C-CrMoV steel is modified version of 15CDV6 steel and is considered as a substitute for ultra high-strength material like maraging steel. This paper deals with study of weld bead dimensions, optimising weld parameters, and heat treatment process to get the maximum strength. In this work, the welding parameters, its response on the variables, and influence on weld properties are studied. The test plates after welding were subjected to liquid penetrant test (LPT), X-ray radiograph. Dimensional measurements were carried on weld beads. Tensile and impact test specimens were cut from these test plates, heat treated, and quenched in different cooling mediums. These test specimensions were subjected to hardness, tensile, and impact testing. The test results were compared to find out the combinations of weld parameters which gives the maximum properties.

Keywords 15CDV6 steel · 0.3%C-CrMoV steel · GTAW · Radiography · LPT · Weld bead dimensions

1 Introduction

15CDV6 [1] (Table 1) steel is high-strength low -alloy steel used in the fabrication of booster motor casings and pressure vessels in aero space applications. For larger

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Table 1 Chemical composition (% in weight)—15CDV6 [1] steel

C	Mn	Si	Mo	V	Cr	S	P	Fe	O_2	H2	N_2
0.12–0.16	0.81–1.0	0.20 max	0.80–0.90	0.20–0.30	1.25–1.50	0.015 max	0.02 max	Bal	70 ppm max	3 ppm max	150 ppm max

space boosters and pressure vessels, new ultra high-strength materials with higher specific strength are explored. So a new alloy known as.

0.3%C-CrMoV [2] steel (Table 2) is developed which is considered to be a cost-effective alternative to maraging steel. In this study, combinations of weld parameters were selected using the principle of Taguchi's design of experiment (DOE) with three levels and four variables. Nine experiments with different combination of weld parameters were carried on the test plates of size 8 mm × 200 mm × 150 mm. As per Taguchi's orthogonal array selection table, L9 orthogonal array was selected. For three levels of current, voltage, variables like root gap, number of passes, welding speed, and types of quenching media were employed. Hardness, ultimate tensile strength, 0.2% proof strength, %elongation, %reduction in area, impact strength were responses. Using the above methodology, nine test plates were welded by varying the current, voltage, root gap, number of weld passes, etc. (Tables 4, 5 and 6). These test plates were inspected by measuring [3] bead width, reinforcement height, depth of penetration (Tables 7, 8 and 9). All the nine test plates were subjected to visual, dimensional, liquid penetrant test (LPT), and X-ray radiography inspections (Table 3).

2 Experimental Methods

Manual GTAW [4] was done on the test plates (Fig. 1) by maintaining weld geometry of V-groove with included angle of 60° and a root face of 1 mm. Nine test plates were welded using the principle of Taguchi's design of experiments. These test plates were inspected by measuring bead width (*B*), reinforcement height (*R*), depth of penetration (*r*), and width (*b*) After visual check, liquid penetrant testing (LPT) and X-ray radiography were taken. The X-ray films were processed, interpreted, and found defect free. Tensile and impact test specimens (Fig. 2a, b, c) were cut by water jet machining and dimensions were maintained as per ASTM-A 370 [5],ASTM E 23 [6] standards.

3 Experimental Procedure

One specimen from each plate was tested to represent the weld property in as welded condition (Idn. T1–T9). Heat treatment was carried out for other specimens in an electrically heated laboratory scale furnace as per the heat treatment cycle shown (Table 10) and the rate of heating 100 °C/hour was maintained during heating. For the test specimens cut from test plates TP-1, 5, 9, the cooling media was forced air, for test plates TP-2, 6, 7, the quenching media was water, for test plates TP-3, 4, 8, the quenching media was oil. Similar simulations of heat treatment process were reported by others [3, 7–11] also. These test specimens after heat treatment were

Table 2 Chemical composition (% in weight)—0.3%C-CrMoVsteel (ESR MOD.15CDV6) [1, 2]

C	Mn	Si	Mo	V	Cr	S	P	Nb	Fe	O_2	H2	N_2
0.27–0.31	0.81–1.0	0.20 max	0.80–0.90	0.20–0.30	1.25–1.50	0.015 max	0.02 max	0.1	Bal	50 ppm max	2 ppm max	125 ppm max

Table 3 Process details for multi-pass welding

Material	0.3%C-Cr MoV steel
Test plate size	8 × 200 × 150 mm
Filler metal [3]	Size ϕ2.5 mm × 700 L, chemical composition same as parent metal
Welding method	Manual GTAW
Welding machine	Lincon pulse TIG
Maximum current	350 A

Table 4 Two-pass welding parameters

Experiment	Current (A)	Voltage (V)	No. of pass	Root gap (mm)	Length of filler wire consumed for 200 mm weld length (mm)	Weight of filler metal deposited (per 100 mm in gms)	Weld speed (mm/min)
TP1	160	19	1st	1	350	13	99
	160	18	2nd	–	420	16	46
TP4	202	20	1st	1.5	680	26	65
	160	19	2nd	–	930	36	47
TP7	200	20	1st	2	970	37	64
	165	18	2nd	-	1040	40	37

Table 5 Three-pass welding parameters

Experiment	Current (A)	Voltage (V)	No. of pass	Root gap (mm)	Length of filler wire consumed for 200 mm weld length (mm)	Weight of filler metal deposited (per 100 mm in gms)	Weld speed (mm/min)
TP2	206	20	1st	1.5	450	17	87
	206	19	2nd	–	550	21	78
	180	18	3rd	–	650	25	71
TP5	206	19	1st	2	550	21	75
	206	19	2nd	–	560	21	63
	180	18	3rd	–	600	23	64
TP8	160	16	1st	1	340	13	71
	160	16	2nd	–	360	14	62
	158	18	3rd	–	550	21	62

Table 6 Four-pass welding parameters

Experiment	Current (A)	Voltage (V)	No. of pass	Root gap (mm)	Length of filler wire consumed for 200 mm weld length (mm)	Weight of filler metal deposited (per 100 mm in gms)	Weld speed (mm/min)
TP3	203	20	1st	2	600	23	98
	203	20	2nd	–	350	13	103
	203	18	3rd	–	525	20	75
	181	18	4th	–	425	16	67
TP6	160	16	1st	1	350	13	56
	159	17	2nd	–	250	10	57
	160	18	3rd	–	350	13	66
	160	18	4th	–	450	17	52
TP9	204	19	1st	1.5	400	15	75
	203	19	2nd	–	350	13	97
	205	19	3rd	–	300	11	105
	180	18	4th	–	600	23	74

Table 7 Weld bead dimensions (in mm) of two-pass welding

Test plates TP 1, TP 4, TP 7	Width—*B*	15/12	14.1/12.1	13.8/11.4
	Height—*H*	2/0.9	1.6/0.9	1.9/0.7
	Penetration width—*b*	9/6.9	7.9/6.9	10.1/6.9
	Penetration height—*h*	1.9/0.8	3.7/2.3	2.8/0.8

Table 8 Weld bead dimensions (in mm) of three-pass welding

Test plates TP 2, TP 5, TP 8	Width—*B*	11/10	11.8/10.1	10.7/10
	Height—*H*	2.0/0.9	2.2.1.0	2.0/1.4
	Penetration width—*b*	7.6/5.0	8.2/5.3	6.5/5.1
	penetration height—*h*	0.8/0.5	1.0/0.6	1.1/0.5

Table 9 Weld bead dimensions (in mm) of four-pass welding

Test plates TP 3, TP 6, TP 9	Width—*B*	11.9/10.7	10.9/9.9	12.3/10
	Height—*H*	1.0/0.4	1.8/0.8	2.5/0.7
	Penetration width—*b*	10.5/5.0	7.0/4.0	6.5/5.1
	Penetration height—*h*	2.6/0.5	2.4/0.4	1.5/0.3

cleaned by wire brushing to remove the heat treatment scaling, corrected to maintain the dimensions by fitting process using hand files.

4 Results and Discussions

Hardness survey [12] carried in all the welded test specimens at the portions of fusion zone (FZ), weld interface (WI) between fusion zone and heat affected zone, heat affected zone (HAZ), on the parent metal, and the values are tabulated below. Table 11 for annealed condition and Tables 12, 13 and 14 and Fig. 1b–d for respective heat treated and quenched conditions (Tables 15, 16, 17, 18, 19, 20, 21 and 22).

Tensile tests [13] were conducted on the specimens (Fig. 2a, b) using 20T capacity computerised UTM machine and 0.2% proof stress was measured using electronic

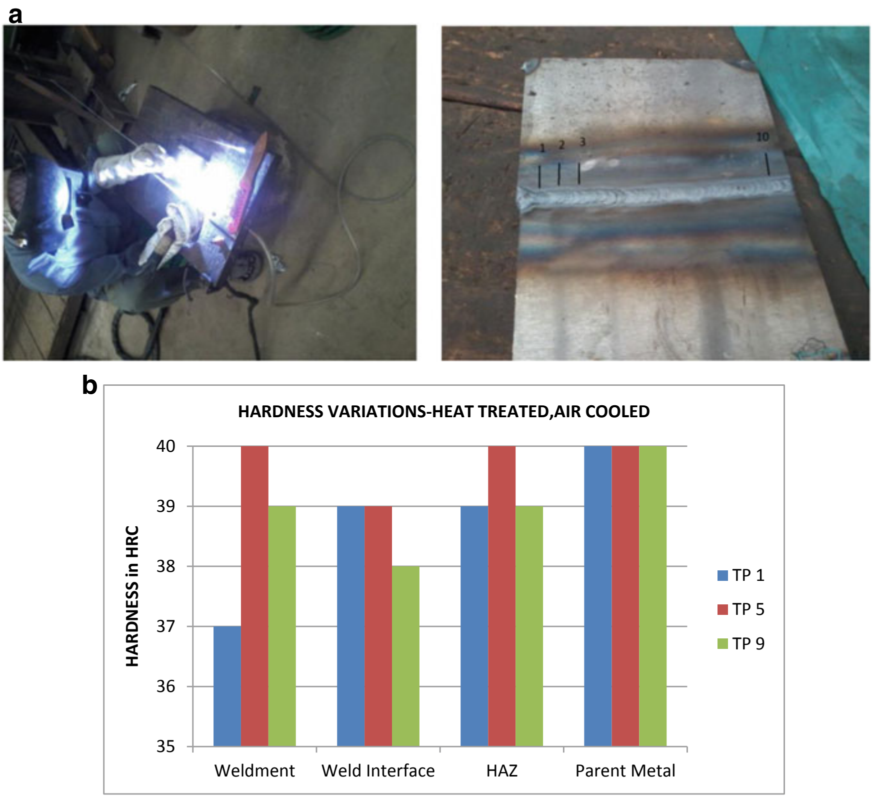

Fig. 1 **a** Weld set up and test plate after welding, **b** Hardness variations in (HRc)-Heat treated, air cooled, **c** Hardness variationds in (HRc)-Heat treated, water cooled, **d** Hardnes variations in (HRc)-Heat treated, oil cooled

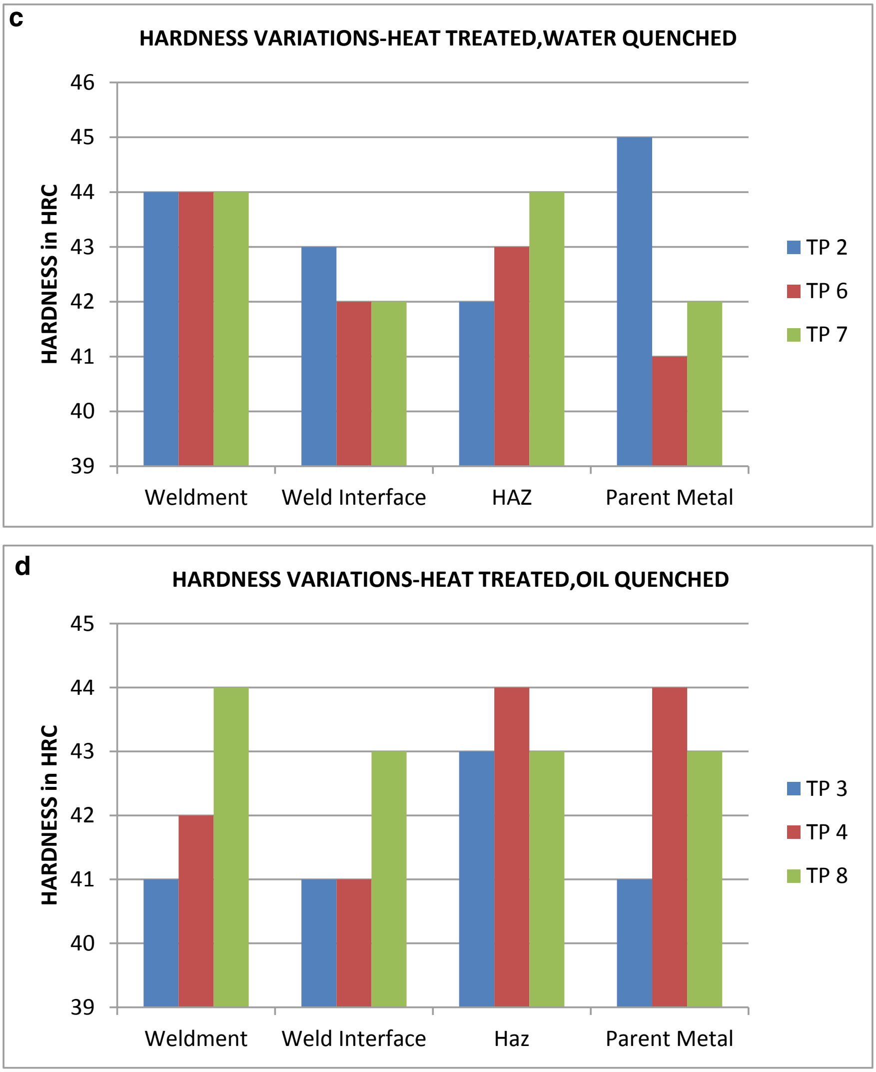

Fig. 1 (continued)

extensometer with autographic recording facility. The tensile test values obtained with different quenching media were tabulated.

The variations of UTS with respect to number of weld passes and root gap at different quench conditions are shown in Fig. 3a, b

Sub-size charpy V-notch [6] impact test specimens (size 55 mm × 10 mm × 7.5 mm, with a notch depth of 2° × 45°, Fig. 2c) were machined and the V-notches were cut using broaching notch cutter machine. Impact testings were carried out at room temperature and the values are given in Figs. 4, 5 and 6.

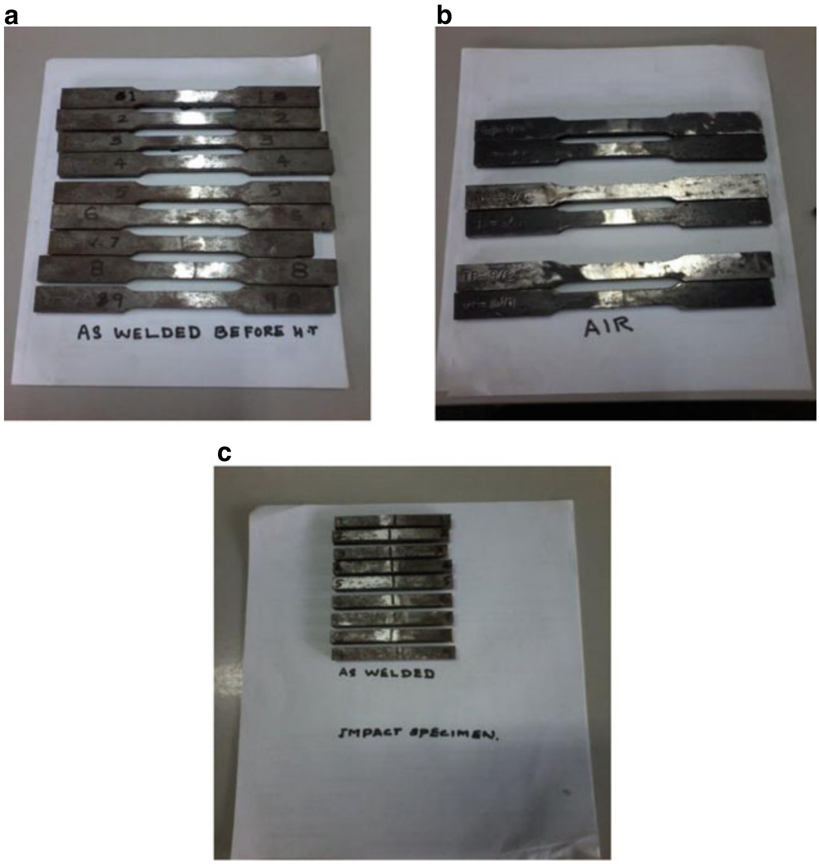

Fig. 2 **a**–**c** Tensile and impact test specimens

Table 10 Heat treatment cycle

Process	Temperature at loading	Temperature at soaking	Soaking time	Quenching/cooling medium
Hardening	<600 °C	920 °C	1 h	Air for TP-1, 5, 9 Water for TP-2, 6, 7 Oil for TP-3, 4, 8
Quench delay	<45 s			
Stress relieving	<200 °C	300 °C	1 h	Air
Tempering	<300 °C	505 °C	2 h	Air for TP-1, 5, 9 Water for TP-2, 6, 7 Oil for TP-3, 4, 8
Quench delay	<45 s			

Table 11 Hardness (in HRC)—As welded condition

Idn No.	Weldment	Weld interface	HAZ	Parent metal (annealed) in BHN (HRC)
T-1	36	38	40	200 (20)
T-2	38	36	40	195 (20)
T-3	37	36	39	205 (21)
T-4	36	37	38	200 (20)
T-5	35	36	38	200 (20)
T-6	36	37	39	195 (20)
T-7	36	37	39	200 (20)
T-8	35	36	38	205 (20)
T-9	36	37	40	200 (20)

Table 12 Hardness (in HRC)—Heat treated, air cooled

Idn No.	Weldment	Weld interface	HAZ	Parent metal portion
TP-1	37	39	39	40
TP-5	40	39	40	40
TP-9	39	38	39	40

Table 13 Hardness (in HRC)—Heat treated, water quenched

Idn No	Weldment	Weld interface	HAZ	Parent metal portion
TP-2	44	43	42	45
TP-6	44	42	43	41
TP-7	44	42	44	42

Table 14 Hardness (in HRC)—Heat treated, oil quenched

Idn No.	Weldment	Weld interface	HAZ	Parent metal portion
TP-3	41	41	43	41
TP-4	42	41	44	44
TP-8	44	43	43	43

Table 15 Mechanical test [13] values—As welded condition (without heat treatment)

	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9
Root gap	1	1.5	2	1.5	2	1	2	1	1.5
Number of passes	2	3	4	2	3	4	2	3	4
UTS: MPa	690	651	657	706	648	695	663	679	688
0.2% PS Mpa	558	479	484	509	459	479	446	521	439
% Elongation	16.2	16.3	16.1	18	16.3	18	18.2	17.8	17.7

Table 16 Mechanical test [13] values—Heat treated, cooling medium—Air

	TP-1/1	TP-1/2	TP-5/1	TP-5/2	TP-9/1	TP-9/2
Root gap	1	1	2	2	1.5	1.5
Number of passes	2	2	3	3	4	4
UTS:MPa	1209	1191	1272	1216	1190	1260
0.2%PS: MPa	1075	1073	1217	1148	1088	1132
% Elongation	12.6	14.4	11.8	12	12.9	12.8
% Reduction in area	30.4	32.7	22.3	28.3	29.1	21

Table 17 Mechanical test [13] values—Heat treated, quenching medium—Water

	TP-2/1	TP-2/2	TP-6/1	TP-6/2	TP-7/1	TP-7/2
Root gap	1.5	1.5	1	1	2	2
Number of passes	3	3	4	4	2	2
UTS: Mpa	1324	1334	1395	1346	1308	1341
0.2%PS Mpa	1268	1287	1323	1323	1267	1306
% Elongation	11.8	10.9	11.9	12	11.8	12
% Reduction in area	23.4	29.4	23.1	24.9	30.9	28.6

Table 18 Mechanical test [13] values—Heat treated, quenching medium—Oil

	TP-3/1	TP-3/2	TP-4/1	TP-4/2	TP-8/1	TP-8/2
Root gap	2	2	1.5	1.5	1	1
Number of passes	4	4	2	2	3	3
UTS: MPa	1295	1307	1404	1403	1430	1404
0.2%PS MPa	1142	1241	1372	1375	1383	1377
% Elongation	11.7	10.5	10.8	12.5	8.5	10.1
% Reduction in area	28	27	23.8	21.4	18.4	16.1

[a] In all the specimens, the location of failure was outside the weldment

Table 19 Impact test [6] values—As welded condition

Impact energy	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9
Joules	27	44	52	25	24	52	28	34	30

Table 20 Impact test [6] values-Heat treated, cooling medium—Air

Impact energy	TP-1/1	TP-1/2	TP-5/1	TP-5/2	TP-9/1	TP-9/2
Joules	16	16	16	18	26	24

Table 21 Impact test [6] values—Heat treated,quenching medium—Water

Impact energy	TP-2/1	TP-2/2	TP-6/1	TP-6/2	TP-7/1	TP-7/2
Joules	16	20	20	18	20	18

Table 22 Impact test [6] values—Heat treated, quenching medium—Oil

Impact energy	TP-3/1	TP-3/2	TP-4/1	TP-4/2	TP-8/1	TP-8/2
Joules	22	18	18	14	16	18

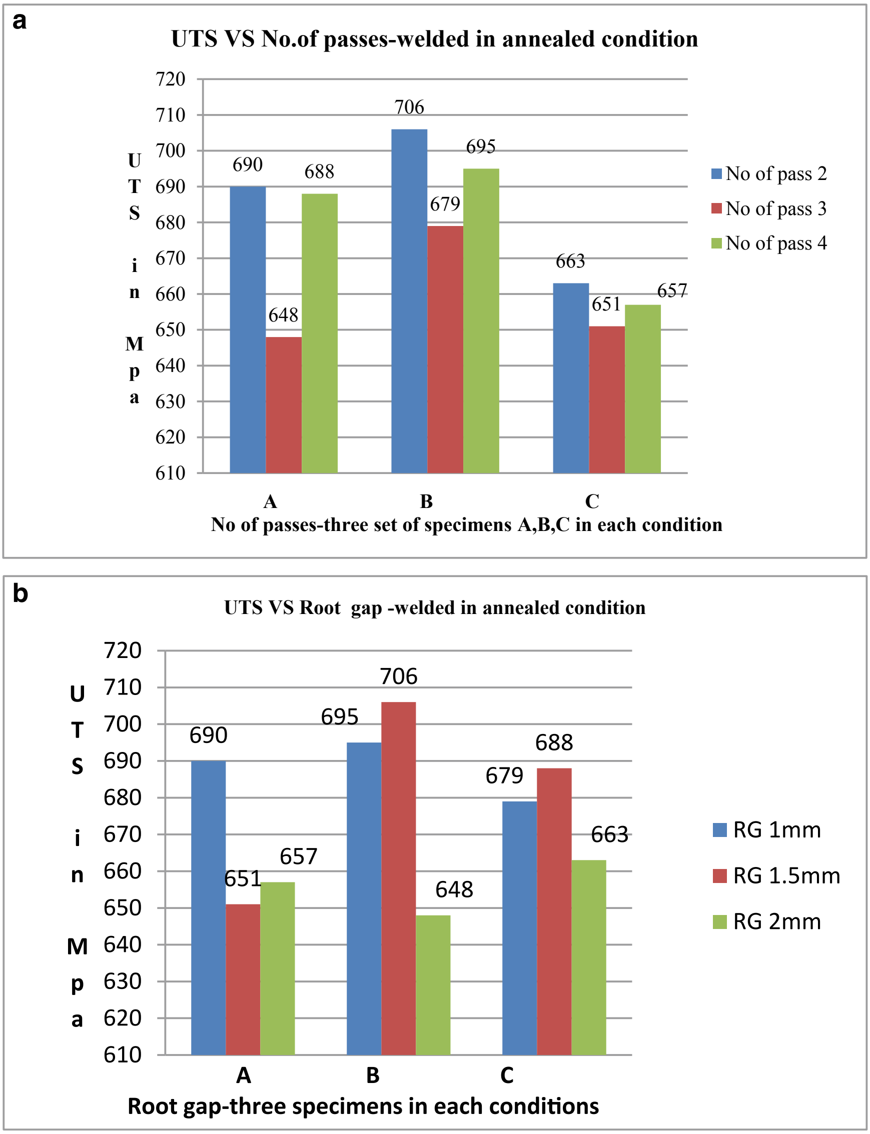

Fig. 3 UTS Vs no. of weld pass in annealed conditions

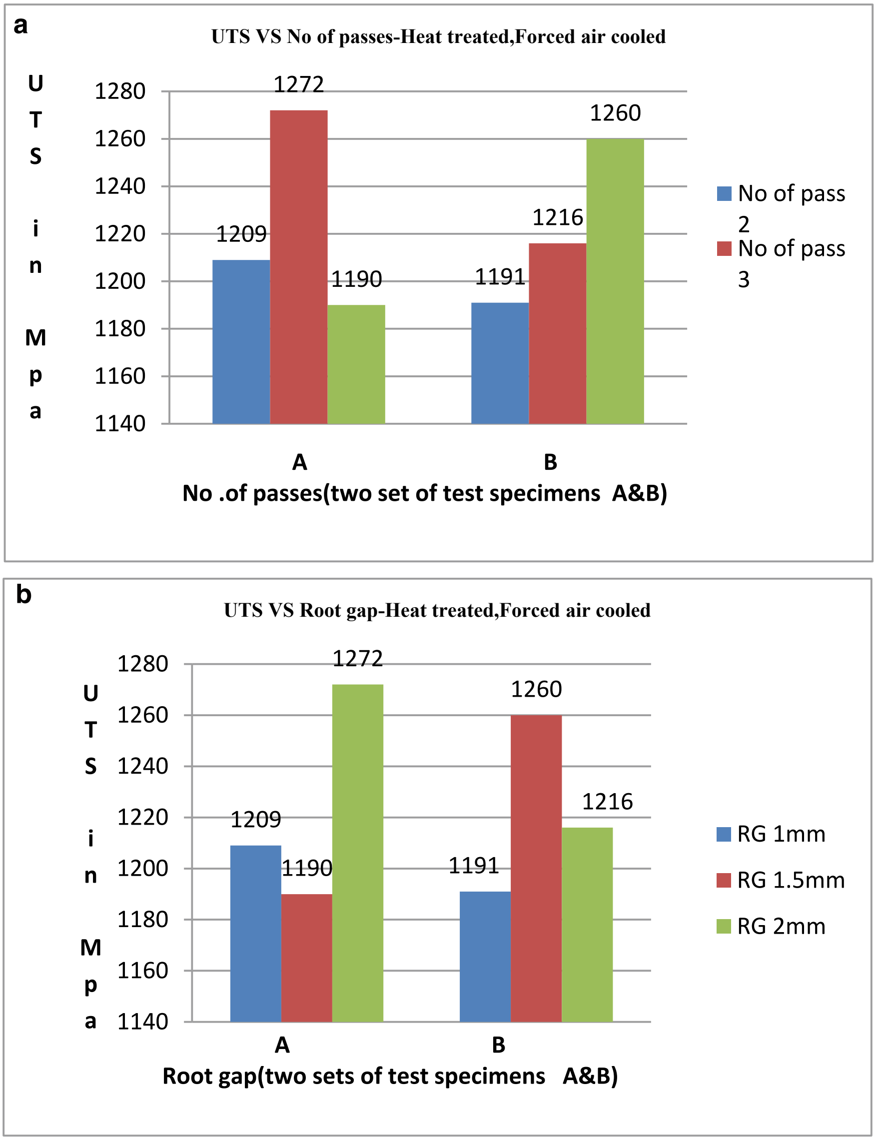

Fig. 4 UTS Vs no. of weld pass, heat treated, air cooled

5 Weld Microstructure in Annealed Condition

Optical microstructure of this material, in the as welded condition, reveals ferrite with carbides (Fig. 7a).

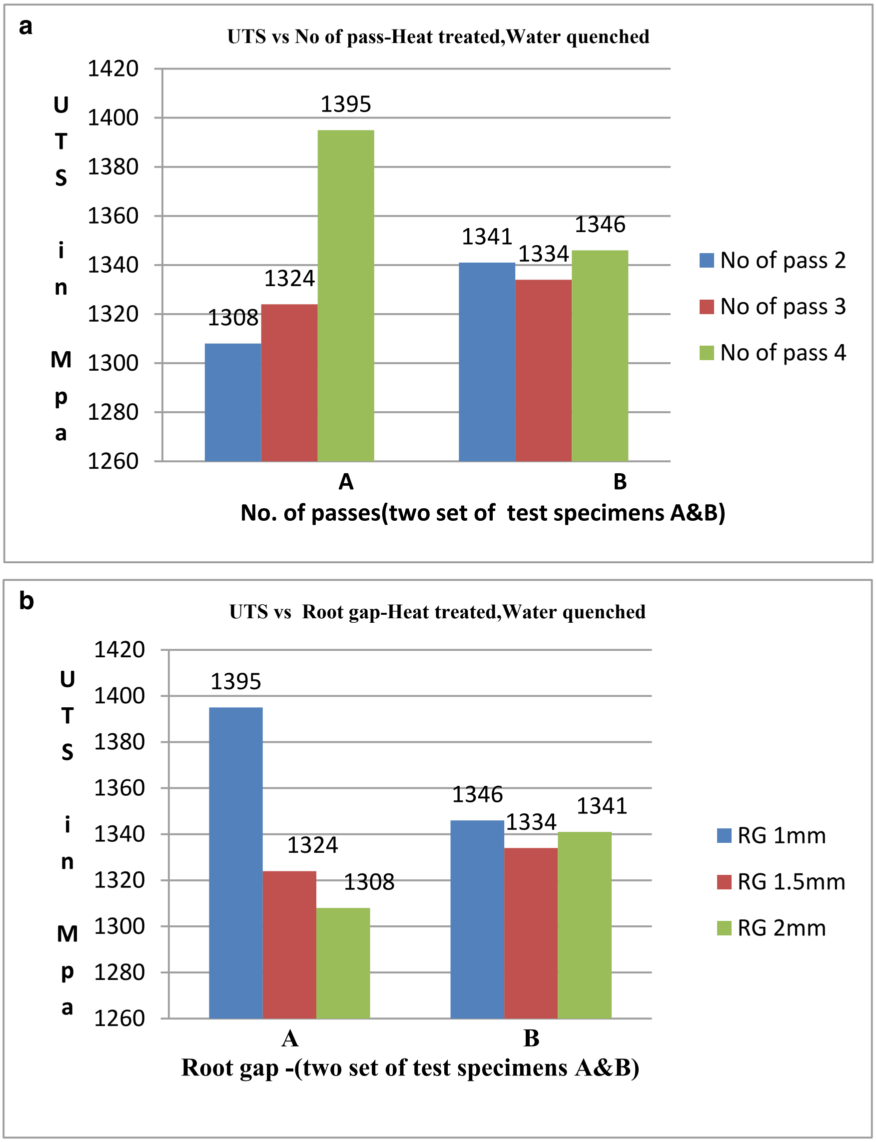

Fig. 5 UTS Vs no. of weld pass, heat treated, water cooled

The optical microstructure of the weldment, heat treated, and quenched in oil and water shows combined microstructure of bainite, martensite in fusion zone (Fig. 7c, d).

The optical microstructure weldment hardened and tempered followed by rapid air cooling shows bainitic structure along with martensite, ferrite, and carbides (Fig. 7b).

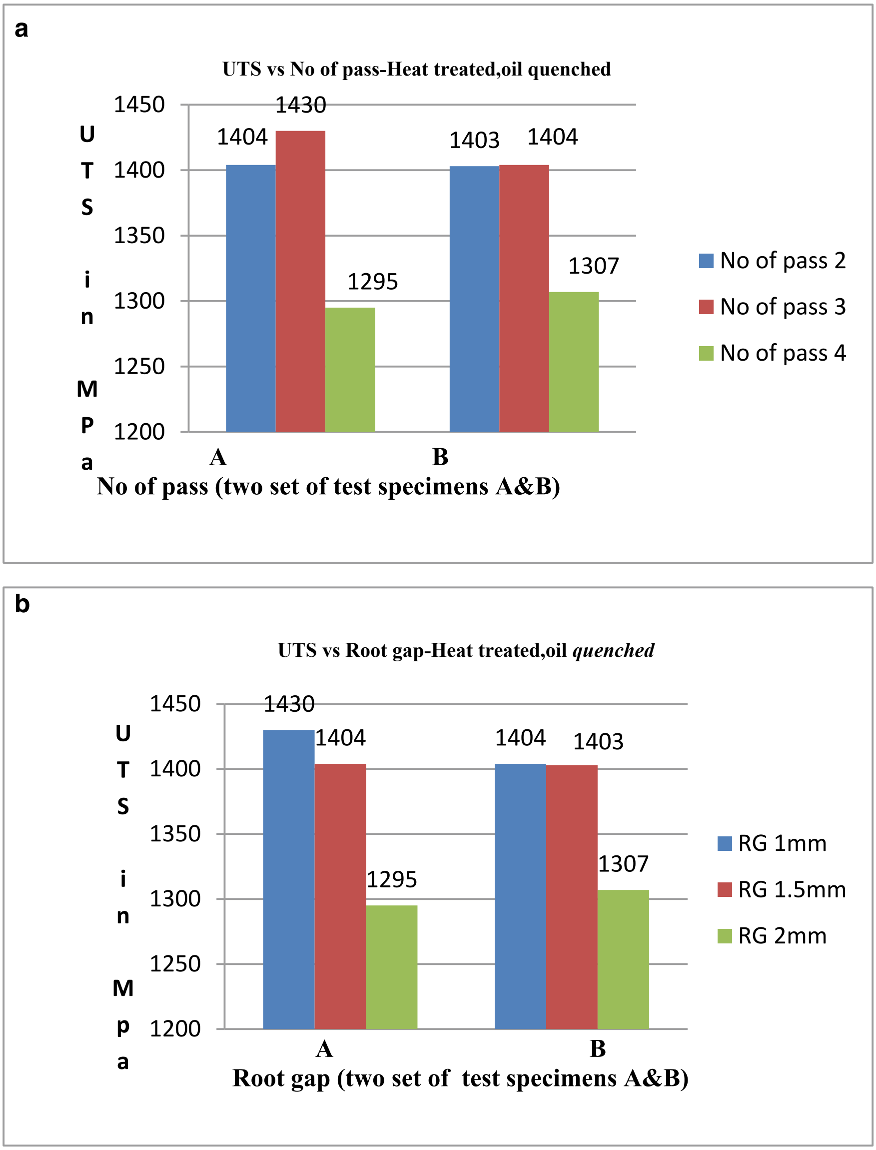

Fig. 6 UTS Vs no. of weld pass, heat treated, oil cooled

Similar microstructure was reported in parent metal weld studies in both annealed and hardened conditions [3, 7–9]

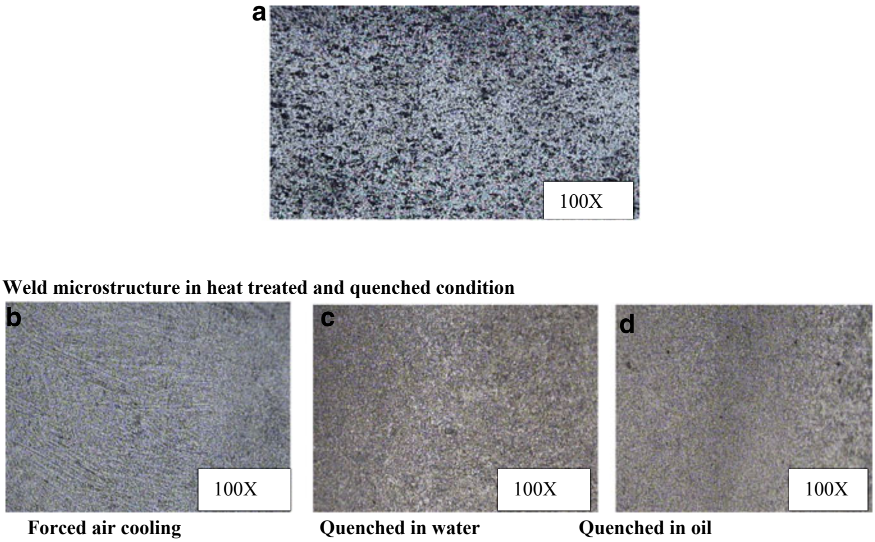

Fig. 7 **a** weld micro structure, welded in annealed condition, **b** weld micro structure, heat treated, air cooled, **c** weld micro structure, heat treated, water cooled, **d** weld micro structure, heat treated, oil cooled

6 Observations

1. The 0.3%C-Cr–Mo-V steel is welded with manual GTA welding in annealed condition gives good bead forming, reinforcement, and penetration.
2. The test plates were welded with different combination of welding parameters, which gave defect free weldment.
3. In multi-pass welding, the weld parameter variations were same irrespective of number of passes.
4. The welding current and voltage required were less when the root gap maintained is 1 mm irrespective of the number of passes.
5. When the root gap is between 1.5 and 2 mm, the current required for the root pass welding and the subsequent passes was more. The closing pass needed lesser current.
6. The rate of filler wire consumption and the welding speed was less when the root gap is less and vice versa.
7. The rate of filler metal deposition was more, when root gap increases, irrespective of number of passes.
8. The dimensional variations of weld bead remain almost same in all the combinations.

7 Conclusions

1. In this work, the 0.3%C-Cr-Mo-V steel of 8 mm thickness is used. These plates were welded by using manual GTA welding by employing the weld parameters as per DOE principle. The welded test plates were subjected to NDT methods, then hardened and tempered and quenched using forced air, water, and oil as quenching mediums.
2. The significant outcome of these work is, in all the cases, the tensile tests specimen rupture occurred at the parent material. This shows the strength of both HAZ and the weldment is not lower than that of parent material. Similar trends of tensile properties were reported by Ramkumar [3] in using PAW process.
3. The weldment attains the hardness (Table 11) when welded in annealed condition even though the parent metal region shows less. This is because of hardening effect of the weldment in multi-pass welding.
4. It is found that oil quenching gives maximum strength. Water-quenched specimens give slightly lower properties. Similar trends in the mechanical properties were reported by P.Ramkumar and others [3, 8, 11]
5. When forced air is used as quenching medium, the values of UTS come down since the rate of cooling is less compared to oil and water. Karthikeyan [7] and others reported the same in Parent metal heat treatment studies.
6. Maximum weld strength was obtained in the combinations of 1 mm root gap with number of passes two to three and oil as quenching medium, (Table 10; Fig. 6a, b)
7. The higher strength of weldment was the result of faster cooling which leads to the formation of higher amount of martensite [8].
8. The maximum impact properties were obtained from the plates welded in annealed condition with multi-pass welding.

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