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ORIGINAL ARTICLE

Welding of quenched and tempered steels with high-spin arc narrow gap MAG system

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Abstract The aim of the study was to evaluate the possibilities of improving the quality and economic efficiency when welding quenched and tempered low carbon low alloy steels with high-spin arc narrow gap MAG system. Mechanical properties of tested welds were excellent, and the amount of welding defects detected by non-destructive testing was very small. The following results were obtained: the welding method of quenched and tempered steels with high-spin arc narrow gap MAG system is an excellent choice. The method improves the weld quality, improves economic efficiency by lowering the joint volume. The properties obtained in the weld joint were found to meet stipulated requirements.

Keywords High-spin arc narrow gap MAG system · Quenched and tempered steels · Mechanical properties

1 Introduction

Quenched and tempered steels are used in military applications owing to high hardness, high strength to weight ratio, and excellent toughness [1–8]. When quenched and tempered low carbon low alloy steels are welded, it is necessary to control the microstructures of both the heat-affected zone and the weld deposit. These grades of quenched and tempered steels are prone to hydrogen induced cracking after welding and they exhibit heat-affected zone (HAZ) softening [1], which leads to poor ballistic performance. Quenched and tempered steel welds must be of good quality especially when used for construction of combat vehicles in military applications. The majority of vessel fabrication is performed by the fusion welding process, which demands for the highest welding quality. Shielded metal arc welding and flux-cored arc welding processes are widely used in the fabrication of combat vehicle construction. HAZ softening exists during welding of quenched and tempered steels and it is inevitable. The degree of softening in the HAZ is a function of the weld thermal cycle (which is a characteristic of the welding process), the kinetics of the phase transformations, and the chemistry of the steel. From the above discussions, it is clear that welding consumables and welding processes have considerable effect on the performance of the quenched and tempered steel joints that are used in military applications.

The increased demands for improving quality and cost efficiency when welding pulp and paper industry and power plant components have set more requirements for used welding technology. Increased wall thicknesses and quality requirements are achieved using only few welding processes. The conventional rotation arc welding can produce good quality welds, but it has its weak point at small deposition rate. Ways for improving the efficiency directly and indirectly can be based on reduced weld volume, increased deposition rate, and higher arc efficiency [9–13].

The GMAW welding method is applicable for the welding of the stainless steels by offering excellent and uniform quality required for the demanding applications. The GMAW welding method is suitable for position welding and therefore it is used for orbital welding of the

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Table 1 Chemical composition of base metal and weld metal, wt.%

Base metal	Fe	Cr	Mn	Mo	Ni	Si	V	C	P	S			
Wt.%	93.41	0.55	0.55	0.425	4.6	0.27	0.06	0.11	0.015	0.01			
Weld metal	Fe	Cr	Mn	Mo	Ni	Si	V	C	P	S	Al	N	Ti
Wt.%	93.85	0.6	1.7	0.6	2.5	0.4	0.2	0.05	0.01	0.01	0.04	$7e^{-7}$	0.035

power plant pipelines. The utilisation of the GMAW welding for thick wall materials has been limited by its low efficiency compared to SAW methods. Use of the narrow gap GMAW welding improves the quality and assures a much better economic efficiency. The advantages attained with the narrow gap GMAW welding compared to traditional methods are: reduced weld volume and shorter welding time, lower heat input, lower incidence of weld metal defects, lower residual stresses, and easy mechanization The advantages attained with the narrow gap GMAW welding set some extra requirements, which are: requires more advanced welding equipment, accurate joint preparation, more expensive shielding gas [9–13] when narrow gap method is used. It is profitable to use narrow groove starting from 12 mm wall thickness. As the number of beads decreases, the arc time and the total welding time are decreased. Consequently, productivity is improved. Also, filler metal consumption is diminished, which increases economic efficiency, especially in the case of welding high-alloyed steels.

Hence, in this study, an investigation has been carried out to study the effect of high-spin arc narrow gap MAG processes on the transverse tensile and impact properties of vessel grade quenched and tempered 10Ni5CrMoV steel joints.

2 Experimental

The narrow gap GMAW welding method was investigated for optimising the quality of quenched and tempered low carbon low alloy steels plate. Quenched and tempered low carbon low alloy steels were welded in flat position. The effect of welding parameters, welding consumables, shielding gases, and groove geometries were evaluated. New welding equipment was developed and video monitoring system for controlling the process was installed. Microstructures of the weldments were examined using optical and scanning electron microscopy. Mechanical properties were examined using tensile, Charpy-V impact toughness and bending tests. Most of the welds were examined by non-destructive testing.

2.1 Materials

The materials used in welding tests are widely used in vessel industry and nuclear power plants. The chemical compositions of these materials are shown in Table 1.

2.2 Welding equipment

The welding equipment used for the tests was mostly from MOTOman, Japan. The total set of equipment used is shown in Table 2. The high-spin arc narrow gap MAG system was developed to meet the requirements for the quality and the maximum wall thicknesses. In Fig. 1 is seen the flat position welding of the quenched and tempered low carbon low alloy steels in the laboratory conditions. In Fig. 2 is seen the orbital welding of quenched and tempered low carbon low alloy steels. The video monitoring system was installed to enable the direct control of the welding

Table 2 Welding equipment used

System components	Function
Power source and optional components	DC GMAW NB-500 cl
	6-DOF robot system cooperated with Motoman-Up20
	2-DOF positioner
Narrow gap welding torch	High-spin arc narrow gap welding torch
Video monitoring system	Colour video camera and video monitor
Computer	Control and documentation

Fig. 1 The flat position welding of the quenched and tempered low carbon low alloy steels

process. When using the video camera and monitor, the accurate positioning of the filler wire and ensuring the adequate wetting of the groove side walls is easy [13, 14]. In Fig. 3 is seen the views available from the video monitoring system.

2.3 Groove geometry

The narrow gap GMAW welding often requires a square groove only. A groove angle (0°–6°) is used only for the distortion compensation, and the selection of the used angle depends on the properties of the base material and wall thickness welded. In Fig. 4 is seen the groove behaviour of the quenched and tempered low carbon low alloy steels and the selected groove geometry.

Fig. 2 The orbital welding of quenched and tempered low carbon low alloy steels

2.4 Welding parameters

The most important parameters affecting the welding process are welding currents, arc voltage, filler wire feeding rate, spin frequency, and travelling speed [9, 14]. Welding currents, arc voltage and travelling speed should be selected so that the heat input remains low and the risk of the lack of fusion is avoided. Selected welding parameters have a strong effect on the weld bead profile. The preferred weld bead profile should have a concave upper surface with adequate wetting on the side walls with a uniform layer thickness. The optimised weld bead profile minimises the risk of the lack of fusion at the side walls (Fig. 5).

Also the effect of the shielding gas was evaluated by comparing argon (Ar), argon–helium 50%/50% (Ar-He 50/50) and argon-helium-oxygen 49.5%/49.5%/1% (Ar-He-O2 49.5/49.5/1).As a result was seen that pure argon does not provide enough wetting on the side walls without increasing welding current and arc voltage significantly. However, pure argon (Ar) is ideal as a start gas. Using Ar-He 50/50 or Ar-He-O2 49.5/49.5/1 as a shielding gas increases the arc temperature and weld pool movement and thereby provides an adequate wetting on the side walls without any need to increase welding current and arc voltage. Welding spatter rate using Ar-He-O2 49.5/49.5/1 is less than that using Ar-He 50/50.

2.5 Test of mechanical properties

Microhardness tests were carried out at a load of 10 kg for targeted regions of the weldment, namely; weld metal (WM), the full quenched zone, and the part of quenched zone, and parent metal were taken for typical weldment zone.

Bend testing (root) was conducted in accordance with GB*3351–1988 on all-welded plates after PWHT. Samples were bent 180° around a former with a diameter 6.7 times the thickness of the plate. The purpose of the bend tests was to qualify the ductility of the weld with PWHT. Bend test samples machined to the required width of 20 mm and the weld reinforcement cannot be removed.

3 Results and discussion

Microstructures of the weldments were examined using optical and scanning electron microscopy. Mechanical

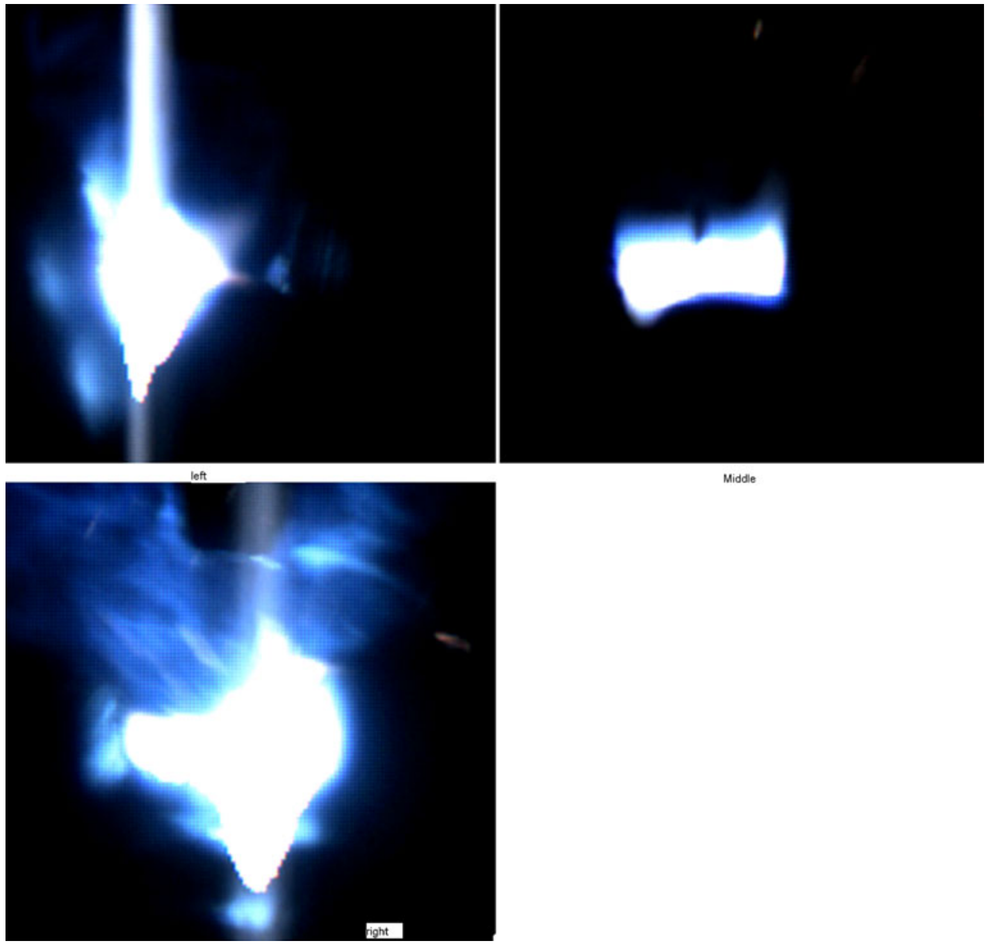

Fig. 3 The views available from the video monitoring system

properties were examined using tensile, Charpy-V impact toughness and bending tests. Most of the welds were examined by non-destructive testing. In Tables 3 is seen some examples of welding parameters.

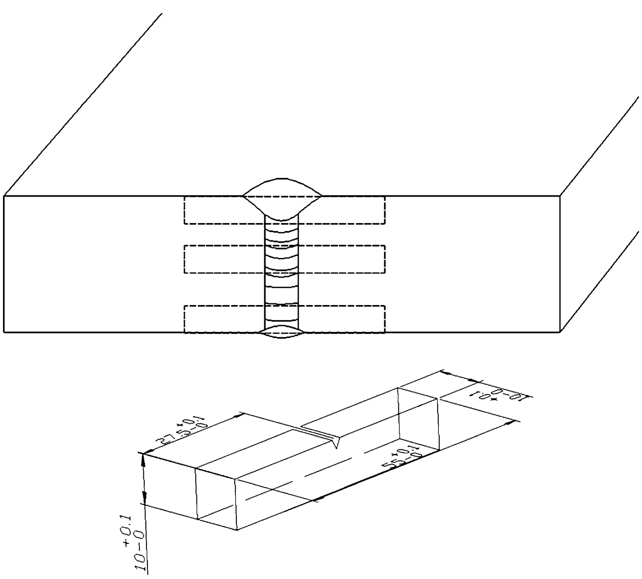

Fig. 4 The groove behaviour of the quenched and tempered low carbon low alloy steels and the selected groove geometry

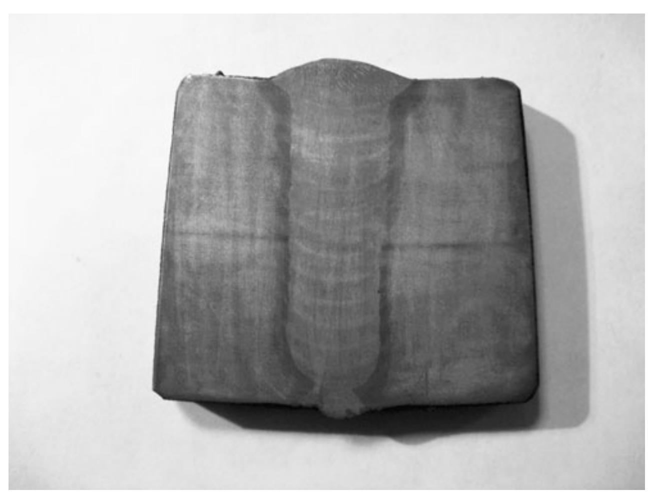

Fig. 5 The optimised weld bead profile

Table 3 Welding parameters were used during welding

Layer	Welding voltage (V)	Welding current (A)	Welding speed (cm/min)	Rotating frequency (Hz)	Deflection angle (°)
1	32	280	0.35	60	4
2	32	280	0.35	60	4
3	32	300	0.35	60	4
4	32	280	0.35	60	4
5	32	280	0.35	60	4
6	32	280	0.35	60	4
7	32	280	0.35	60	4
8	32	280	0.35	60	4
9	32	280	0.35	60	4
10	32	280	0.35	60	4
11	32	260	0.35	60	4
12	32	280	0.35	60	4
13	32	280	0.35	60	4
14	34	280	0.35	60	4

3.1 Metallography

The microstructure of the joints was examined at different locations, and the optical micrographs taken at different regions of the welded joints are displayed in Fig. 6. From the micrographs, it is clear that all the joints invariably contain three distinctive regions, which are the WM zone, the full quenched zone, and the part of

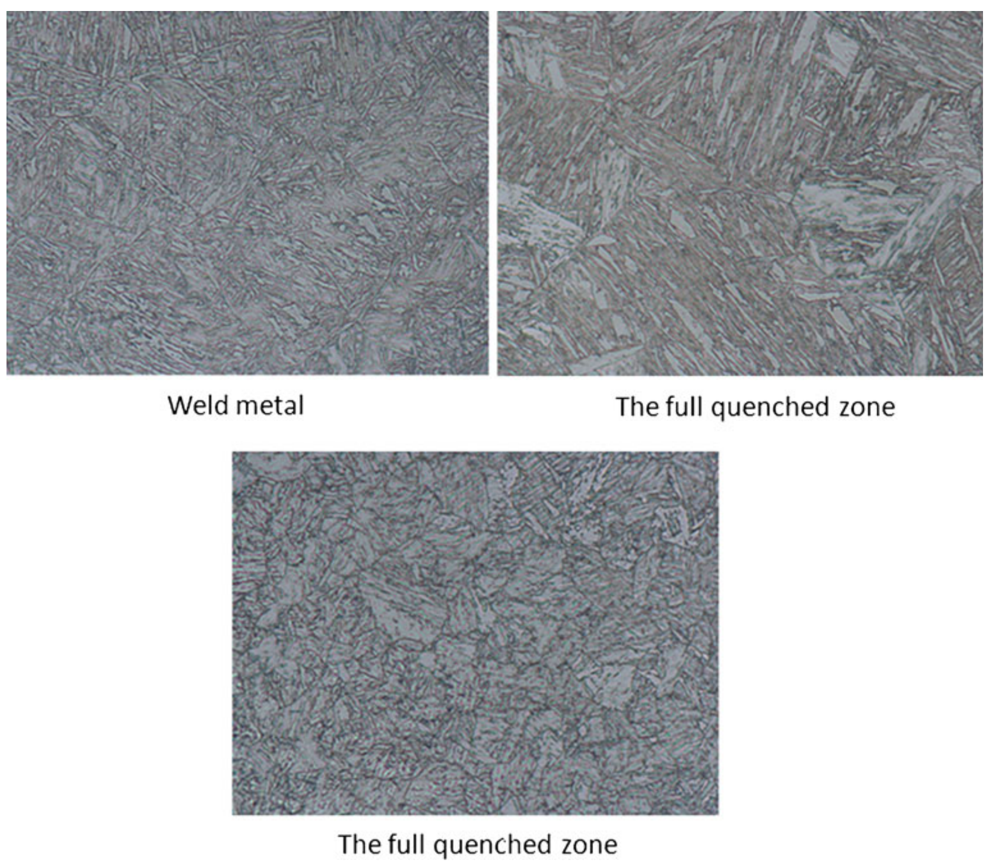

Fig. 6 The microstructure of the joints

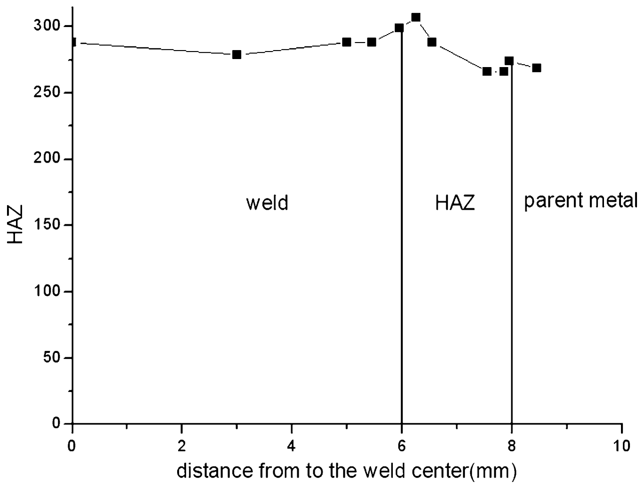

Fig. 7 The hardness characteristic of the joint (the distance of the hardness point from the upper surface is 2 mm)

quenched zone. The micrograph, taken at the weld metal zone of the welding joint, exhibits skeletal acicular ferrite in plain austenitic matrix. The HAZ microstructure adjacent to the fusion line appeared to be an aligned structure consisting of parallel bainitic ferrite laths separated. The air cooling of the HAZ from high austenitising temperature and relatively short cooling time was expected to produce coarse bainite structure. According to them, a combination of large austenite grain size and a limited number of nuclei sites give rise to coarse transformation structures.

3.2 Mechanical properties

The hardness characteristic of the joint was presented in Fig. 7. The soft degree was very small in HAZ zone. The transverse tensile properties, impact properties of welded joints, were evaluated, and are presented in Table 4. During tensile test, all the specimens (joints) were found to fracture in between weld line and base metal or in weld seam. From the results, with the heat input increasing, the tensile intension first increased and then decreased. The softening degree is relation to the tensile intension. In condition of small softening degree, the softening degree cannot influence the tensile intension.

Table 5 Non-destructive testing of weldment

Weldment	Inspecton method	Defects	Type of defect
10Ni5CrMoV	Radiograghic testing	–	Lack of fusion

3.3 Non-destructive testing

The non-destructive testing was done for the most of the test welds using ultrasonic or radiographic testing. When the inspection of quenched and tempered low carbon low alloy steels using the conventional radiograghic testing was not able to provide accurate results, was used. The results of the ultrasonic testing of quenched and tempered low carbon low alloy steels are shown in Table 5.

4 Conclusions

The study was to evaluate the possibilities of using the high-spin narrow gap GMAW welding method to improve the quality and economic efficiency when welding quenched and tempered low carbon low alloy steels. The obtained results can be summarised as follows:

1. The high-spin arc narrow gap MAG method is an excellent choice for welding thick quenched and tempered low carbon low alloy steels. The method improves the weld quality, improves economic efficiency by lowering the joint volume and filler wire consumption, but it requires more accurate joint preparation and more expensive shielding gas.
2. Using Ar-He-$O_2$49.5/49.5/1 as a shielding gas can provide an adequate wetting on the side walls without increasing welding current and arc voltage.
3. The weld joint was found to possess an adequate strength. The joints were found to fracture in between weld line and base metal or in weld seam. The impact toughness of the HAZ was found to be superior to that of the WM.
4. The properties obtained in the weld joint were found to meet stipulated requirements.

Table 4 The transverse tensile properties, Impact properties of welded joints

Weldment	R_m (MPa)	%El	%Re	CVN (−50°C)						Bending angle 180°	
				Upper		Middle		Bottom		Upper	Bottom
				Weld	HAZ	Weld	HAZ	Weld	HAZ		
10Ni5CrMoV	864.3	15	32	95	203	89	152	88	124	No defects	No defects

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