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Effects of pulsed Nd:YAG laser welding parameters and subsequent post-weld heat treatment on microstructure and hardness of AISI 420 stainless steel

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ABSTRACT

Martensitic stainless steels are often used in cases where high strength and medium corrosion resistance are required. In this study, pulsed Nd:YAG laser welding of AISI 420 martensitic stainless steel is considered. Welding of samples were carried out autogenously. The spacing between samples was set to almost zero. All samples were butt welded. The effect of welding parameters such as voltage, laser beam diameter, frequency, pulse duration, and welding speed on the weld dimensions were investigated and the optimum values were obtained for the 450 V voltage, 0.6 mm focal diameter, 6 Hz frequency, 5 ms pulse duration and 1.5 mm/s welding speed. Microstructure of weld pool and heat affected zone (HAZ) were investigated by optical microscopy (OM) and scanning electron microscopy (SEM). Micro-hardness studies were also carried out. The results showed the presence of some remaining delta-ferrite in the martensitic weld structure and coarsening of $M_{23}C_6$ carbides in HAZ. The magnitude of hardness in the HAZ was higher than that of the weld zone. To reduce the hardness of weld and HAZ and to increase the toughness in these regions, two types of post-weld heat treatments (PWHTs) were carried out. In type 1, samples tempered for 2 h. In type 2, samples austenitizied for 0.5 h at 1010 °C and then tempered for 2 h. In order to achieve high strength and toughness, optimum temper temperatures for type 1 and 2 heat treatments were obtained for 595 and 537 °C, respectively. The results showed higher toughness for type 2 than type 1.

1. Introduction

Nd:YAG laser welding is an joining technology which is of much interest to automotive, electric, and electronic industries [1]. Nd:YAG pulsed laser welding is expected to be the method of choice because it allows more precise heat control compared with other processes. Moreover, it reduces the width of heat-affected zone (HAZ), residual stress and the presence of discontinuities [2].

Martensitic stainless steels (MSs) are commonly used for manufacturing components with excellent mechanical properties and moderate corrosion resistance; hence, they can work under high and low temperatures. Unlike other stainless steels, their properties could be changed by heat treatment; therefore these steels usually are used for a wide range of applications such as steam generators, pressure vessels, mixer blades, cutting tools and offshore platforms for oil extraction [3]. In the annealed condition (as received), MSs have a microstructure containing spherodized carbides in a ferritic matrix.

Martensitic stainless steels are seldom welded because of their high hardenability and susceptibility to hydrogen induced or cold cracking. In addition, existence of remaining delta-ferrite in martensitic weld structure has adverse effects on mechanical property [4]. Another major problem in welding of martensitic stainless steels is increase of hardness in the HAZ. The high-temperature HAZ will be in the "as-quenched" condition after welding, regardless of the prior condition of the material. In addition, the hardness in the HAZ is very much independent of the cooling rate over the temperature range experienced in common arc-welding practices. Such high hardness values render the material prone to cracking during fabrication, the selection of appropriate preheating levels and welding procedures is critical to the success of the welding process [5]. Due to low heat input in the Nd:YAG pulsed laser welding and good protection, susceptibility to cracking in martensitic stainless steel is low and HAZ is very small.

Materials that have poor toughness are potentially subjected to catastrophic brittle failure under dynamic loading. For reduction of hardness, increasing of toughness and reducing amount of hydrogen and residual stresses, postweld heat treatment (PWHT) is almost always required for martensitic stainless steels; specially for AISI 420 and 440 with carbon levels more than 0.15 wt%. PWHT is normally performed in the range 480–750 °C. The timing of PWHT is depended upon section thickness, but normally 30 min to 2 h is sufficient. PWHT of weld martensitic microstructure cause to transform some of the martensite to ferrite and fine carbide

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Table 1
Effect of PWHT on mechanical property of 420 stainless steel weld metal produced by submerged arc welding [4].

Tempering temperature (°C)	Hardness (Rockwell C)	Tensile strength (MPa)	Elongation (%)
As weld	52	–	–
425	48	1578	2
480	48	1364	3
535	36	1040	15
600	30	971	15
650	27	882	17

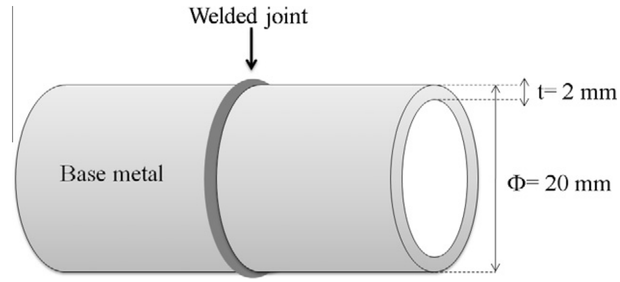

Fig. 1. The schematic drawing of cylindrical samples and welded joint.

which in turn results in improving toughness and ductility. For fully optimize property relative to the base metal, it is advisable to carry out solution heat treatment (SHT) for the entire structure, and then performed quenching and tempering heat treatments. The SHT would re-austenitize the entire structure, dissolve all of the ferrite in the weld metal and result in a uniform martensitic structure. Various tempering treatments can then be used to achieve desired strength, ductility and toughness [4].

Many studies were carried out in the literature on the welding and PWHT of martensitic stainless steel however, few researches were performed on the laser welding of martensitic stainless steel. Khana et al. [6] studied the effects laser power, welding speed and laser beam diameter on bead geometry and mechanical properties of the weld of AISI 440FSe and AISI 416 martensitic stainless steels. In this study, specimens were welded circularly in an overlap joint configuration using Nd:YAG continuous wave laser, in which laser power and welding speed were varied in the range 800–1100 W and 4.5–7.5 m/min. They showed that laser power and welding speed are the most significant factors affecting the weld bead geometry. In this study, the maximum magnitude of hardness in the HAZ was found to be about 700 Hv. In addition, Vishvesh et al [7] investigated the resistance spot welding of AISI 420 martensitic stainless steel. The effects of welding current of resistance spot welding and post-heating parameters on nugget dimension, tensile shear strength, cross tension strength and hardness were investigated. The results of their study showed that the weld microstructure was martensitic and had reached the maximum hardness of 623 Hv. Lippold and Kotecki [4] investigated the effect of tempering temperature on the mechanical property of a continuous caster roll overlaid by submerged arc welding with 420 stainless steel. PWHT was performed in the range 425 °C to 650 °C and PWHT times of 2 h. Table 1 presents mechanical property of 420 stainless steel weld metal produced by submerged arc welding, in some tempering temperature. The results show that increase of tempering temperature up to 480 °C do not change the mechanical property very much, however in higher tempering temperature, the reduction in hardness and strength, and increase in ductility, with increasing PWHT temperature are readily apparent. According to the [4], the optimum tempering temperature for achieving to high hardness and also high strength and ductility, is 535 °C.

This paper investigates the Nd:YAG pulsed laser welding of AISI 420. The effects of voltage, diameter of beam, frequency, pulse duration, and welding speed on the weld dimensions are investigated. The purpose of this study is to achieve the discontinuity-free weld with appropriate dimensions and good mechanical properties.

2. Experimental procedures

AISI 420 stainless steel rod with 20 mm in diameter were used in this investigation for making cylindrical specimen. The schematic drawing of cylindrical samples that are manufactured by turning, are shown in Fig. 1. Chemical composition and mechanical properties of AISI 420 stainless steel are tabulated in Tables 2 and 3, respectively. The Nd:YAG pulsed laser welding was carried out with an SW-1 micro-laser machine. The maximum average power of laser used was 100 W. There was no surface preparation for samples and the samples were butt welded (Fig. 1). The Nd:YAG pulsed laser welding parameters investigated is shown in Table 4. For all tests, the argon gas with the 99.99% purity and gas flow gas of 10L/min was used. The samples were then cut in cross section. The etching process was performed by immersion of the samples in 10 mL ethanol, 10 mL H_2O, 7 mL HNO_3, and 5 mL HCL. In this study, the micrographs of the weld pool of the samples that undergone various welding parameters were compared by optical

Table 2
Chemical composition of AISI 420 stainless steel (wt%).

C	Mn	Si	Cr	Ni	Fe
0.186	0.34	0.458	13.44	0.257	Rem.

Table 3
Mechanical properties of AISI 420 stainless steel in the annealed condition.

Alloy nominal composition	Hardness (Hv)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
AISI 420	241	350	650	25

Table 4
The parameters for laser welding process.

Sample no.	Pulse voltage (V)	Focused beam diameter (m)	Pulse frequency (Hz)	Pulse duration (ms)	Welding speed (mm/s)
1	375	0.7	6	5	1.5
2	400	0.7	6	5	1.5
3	425	0.7	6	5	1.5
4	450	0.7	6	5	1.5
5	475	0.7	6	5	1.5
6	425	0.5	6	5	1.5
7	425	0.6	6	5	1.5
8	425	0.8	6	5	1.5
9	425	0.9	6	5	1.5
10	425	0.7	6	3	1.5
11	425	0.7	6	4	1.5
12	425	0.7	6	6	1.5
13	425	0.7	6	7	1.5
14	425	0.7	3	5	1.5
15	425	0.7	4	5	1.5
16	425	0.7	5	5	1.5
17	425	0.7	7	5	1.5
18	425	0.7	8	5	1.5
19	425	0.7	6	5	0.75
20	425	0.7	6	5	2