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Influence of aging temperature on strength and toughness of laser-welded T-250 maraging steel joint

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ABSTRACT

This paper presents an investigation on the strength and toughness of laser-welded T-250 maraging steel joint, aimed at elucidating the influence mechanism of aging temperature on microstructures and mechanical properties of the joints. The results showed that as the aging temperature increased, the ultimate tensile strength of welded joints increased, reaching a maximum of 1640.5 MPa at 520 °C, and then decreased. The static toughness of welded joints decreased at first and increased later with the aging temperature increasing. The minimum of 38.8 MJ m^{-3} for the static toughness was obtained at 560 °C. There were two types of reverted austenite respectively distributing in grain boundaries and in the matrix of martensite, due to the change of aging temperatures. This study underscores that the Ni_3(Ti, Mo) precipitate and reverted austenite are the critical factors influencing the strength and toughness of welded joints. The Ni_3(Ti, Mo) precipitate in the weld metal improves the strength of welded joints remarkably as its volume fraction increases. The reverted austenite in grain boundaries is harmful to the toughness of welded joints, while the reverted austenite in the matrix is beneficial to the toughness of welded joints because of its finely dispersive distribution and its ability to prevent crack propagation. Increasing the amount of reverted austenite in the matrix is an effective way to improve mechanical properties of laser-welded maraging steel joints.

1. Introduction

Compared with the conventional carbon-hardened steel, maraging steel possesses high strength/weight ratio and high fracture toughness because of the Fe-Ni martensite with high dislocation density and a plenty of strengthening particles such as Ni_3Ti and Ni_3Mo [1–3]. Maraging steel has widely used in aerospace and navigation [1,2]. T-250, a Ti-strengthened maraging steel with the strength as high as 250 Ksi, was developed to replace Co-strengthened maraging steel and reduced the cost considerably [4,5]. It has an increasing application in solid rocket motor cases and centrifugals of uranium enrichment [6–8]. Its unique weldability in the solutionized condition followed by post-weld aging treatments at a relatively low temperature makes itself attractive for fabrication of large welding structures [9,10]. In the present studies, maraging steel has been welded by several methods [11–13]. Gas tungsten arc welding is generally employed. But the strength and toughness of welded joints are both lower than those of the parent metal [14]. There is some evidence that the friction stir welding (FSW) can obtain welded joints with a high toughness, but with a low strength due to grooves and voids in the weld [15]. In recent years, with low heat input processes such as plasma arc welding, electron beam welding and laser beam welding, high joint efficiencies can be achieved, especially the joint efficiency being over 95% by laser beam welding [13,16–19]. Nevertheless, the mismatch of high strength and low toughness is a serious and urgent problem that needs to be solved, which limits the applications of maraging steel as a structural material for aerospace and defense industries.

In most welded structures of maraging steels, the failure has occurred in the weld metal. The low strength and toughness of welded joints are attributed to segregation of elements and the associated formation of titanium carbide and nitride inclusions [20,21]. Especially when the heat-treatment temperature is higher, such as above 820 °C, the precipitates of carbides or carbosulfides have a significant influence on the mechanical properties of maraging steel [22,23]. So the changes of microstructures like precipitates and reverted austenite have received considerable

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attention. However, the roles of these phases, particularly for the reverted austenite, played on the strength and toughness of welded joints are not thoroughly studied. For the welding of maraging steels, such reversion to austenite usually follows precipitation during aging [18]. It also has been found that the austenite formation may even precede precipitation of intermetallic compounds at some temperature [24]. The precipitates can improve the strength [24,25], while the influence of reverted austenite on material behavior is still controversial. D. T. Peters regards that the reverted austenite is important to fatigue and corrosion cracking [26]. In terms of toughness, H. J. Rack considers that the reverted austenite is beneficial to enhance fracture resistance because of the crack blunting effect. Besides, some researchers point out that the fracture toughness is independent of the volume fraction of reverted austenite [27]. Furthermore, the reverted austenite goes for retarding the diffusion of hydrogen to reduce the sensitivity of hydrogen embrittlement in the study of literature [28]. However, according to the researches, it is deemed that the reverted austenite is harmful to the toughness due to its inconsistent deformation with the matrix [12,17,29]. Therefore, the effect of reverted austenite has not been confirmed.

In response to the aforementioned problems, this work was motivated to investigate the influence of aging temperature on the mechanical properties of laser-welded T-250 maraging steel joint. The microstructures were analyzed to explore its relationship with the strength and toughness of welded joints aged at different temperatures.

2. Experimental procedure

The T-250 maraging steel was produced with normal chemical composition of Fe-0.007C-19Ni-3.0Mo-1.5Ti-0.10Al-0.30Cr (wt%). Aluminum and chromium were added to improve the resistance to oxidation and corrosion. The steel was forged at 1200 °C and then annealed at 830 °C for one hour followed by air cooling (AC). The specimens were supplied with dimensions of 50 mm × 50 mm × 2 mm. Laser welding was carried out using an IPG YLS-2000 fiber laser system with optimized processing parameters listed in Table 1. The welded joints were subjected to the post-weld aging treatments of 420 °C, 440 °C, 460 °C, 480 °C, 520 °C, 560 °C, 600 °C and 640 °C, all held for 3 h and followed by AC.

Tensile specimens were finished with the dimensions as shown in Fig. 1. The tensile tests were conducted using the auxiliary device of Gleeble thermal/mechanical simulation testing machine (Gleeble 1500D). The tensile stress-strain curve was acquired to obtain the ultimate tensile strength (σ_b) and static toughness (U_{OT}), which could represent strength and toughness of the welded joint, respectively [30]. Because the static toughness has a positive correlation with the impact toughness and fracture toughness for metal materials at room temperature [31–33]. The static toughness was obtained from the integrated area calculated by the following equation [32]:

$$U_{OT} = \int_0^{\varepsilon_f} \sigma d\varepsilon \tag{1}$$

where U_{OT} is the static toughness, ε_f is the total strain after the fracture, σ is the real-time stress, ε is the real-time strain.

Hardness was performed by the Vickers hardness tester with the parameters of 300 g/15 s To observe the microstructures, the welded joints were polished to 0.05 μm and etched with modified Fry's reagent (50 ml HCl+25 ml HNO_3+1 g $CuCl_2$+150 ml H_2O). Optical microscopy (OM), electron probe microanalysis (EPMA) and scanning electron microscopy (SEM) combined with energy dispersive spectrometer (EDS) were used to analyze the phases and chemical compositions. The microstructures of the weld metal aged at 560 °C were analyzed with transmission electron microscopy (TEM). TEM samples were electropolished to thin foils with a solution of 5% perchloric acid. The voltage and temperature of the automatic twin-jet electropolishing were 30 V dc and −20 °C.

Table 1
Laser welding parameters performed in the experiment.

Laser power	2000 W
Travel speed	3 m/min
Focusing lens	Cu
Focal length	200 mm
Wavelength	1060 nm
Diameter of focal point	0.13 mm
Defocus	0 mm
Front gas flow rate	20 L/min, Ar
Back gas flow rate	5 L/min, Ar

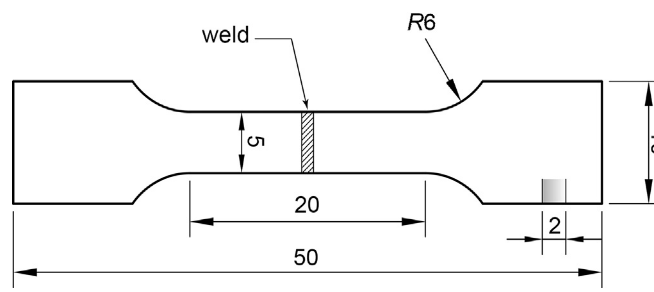

Fig. 1. Dimension of the tensile specimen (unit: mm).

3. Results

3.1. Mechanical properties

Tensile mechanical properties of welded joints aged at different temperatures is acquired with tensile tests as shown in Table 2. The ultimate tensile strength and static toughness vary obviously as the aging temperature increases, which are shown in Fig. 2. When the aging temperature is low, like 420 °C, the ultimate tensile strength is very poor, but the static toughness is close to that of the applied parent metal. When the aging temperature increases, the ultimate tensile strength increases gradually. At the aging temperature of 520 °C, the ultimate tensile strength reaches the maximum of 1640.5 MPa, which is 99.6% of that of the applied parent metal. Above 520 °C, the ultimate tensile strength begins to decrease. However, the static toughness decreases at first, dropping to the minimum of 38.8 MJ m^{-3} at 560 °C, and then increases as the aging temperature increases. The ultimate tensile strength

Table 2
Tensile mechanical properties of welded joints aged at different aging temperatures.

T /°C	σ_b / MPa	U_{OT} / (MJ m^{-3})	F-L
420	1133.6	65	WM
440	1238.5	54.4	WM
460	1542.7	50.9	WM
480	1618.5	47.9	WM
520	1640.5	43.2	WM
560	1506.3	38.8	WM
600	1255.7	61.5	WM
640	1112.5	74.5	WM
APM	1646.8	67.8	——

Note: T-aging temperature, σ_b- ultimate tensile strength, U_{OT}-static toughness, F-L-fracture location, APM-applied parent metal (aged at 480 °C), WM-weld metal.