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Strength and Toughness of T250 Maraging Steel Laser-Welded and Aged Joints (Post-print)

Authors: Li Kun, Shan Jiguo, Wang Chunxu, Zhiling Tian

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Abstract

Fiber laser welding and aging treatment were performed on T250 maraging steel to investigate the strength and toughness of joints under pre-weld aging and post-weld aging conditions, and the underlying reasons were analyzed. The results indicate that the pre-weld aged joint exhibits poor strength and toughness, with its tensile strength being 62% of that of the aged base material and its static toughness being 28%; in contrast, the post-weld aged joint demonstrates superior strength and toughness, achieving 98% of the tensile strength and 71% of the static toughness of the aged base material. The weld zone is identified as the critical region influencing the strength and toughness of welded-aged joints, with the dispersed Ni3(Ti, Mo) precipitate particles in the weld being the fundamental cause for the superior strength and toughness of the post-weld aged joint compared to the pre-weld aged joint. The Ni3(Ti, Mo) precipitates are beneficial to the tensile strength and static toughness during the elastic deformation stage of the joint, while exerting a dual effect on the static toughness during the plastic deformation stage. Grain boundary reverted austenite has minimal influence on the tensile strength and static toughness during the elastic deformation stage, but proves detrimental to the static toughness during the plastic deformation stage of the joint.

Full Text

Preamble

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STRENGTH AND TOUGHNESS OF T250 MARAGING STEEL

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JOINT HYBRID-TREATED WITH LASER WELDING AND AGING

Li Kun[1], Shan Jiguo[1,2], Wang Chunxu[3], Tian Zhiling[3]

[1]Laser Processing Research Center, Department of Mechanical Engineering, Tsinghua University, Beijing 100084
[2]Key Laboratory for Advanced Materials Processing Technology, Ministry of Education, Tsinghua University, Beijing 100084
[3]Institute for Special Steel, Central Iron & Steel Research Institute, Beijing 100081

Correspondent: SHAN Jiguo, Professor
Tel: (010)62773798, E-mail: shanjg@mail.tsinghua.edu.cn

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Abstract

Fiber laser welding and aging treatment were performed on T250 maraging steel to investigate the strength and toughness of welded joints under pre-weld aging and post-weld aging conditions, and the underlying mechanisms were analyzed. The results show that joints subjected to pre-weld aging exhibited poor strength and toughness, with tensile strength and static toughness reaching only 62% and 28% of those of the aged base metal, respectively. In contrast, joints subjected to post-weld aging demonstrated superior strength and toughness, achieving 98% of the aged base metal' s tensile strength and 71% of its static toughness. The weld zone was identified as the critical region controlling the strength and toughness of hybrid-treated joints. The fundamental reason for the superior performance of post-weld aged joints lies in the dispersion of fine Ni_3(Ti, Mo) precipitates within the weld metal. These Ni_3(Ti, Mo) precipitates were beneficial to tensile strength and static toughness during the elastic deformation stage, but exerted a dual effect on static toughness during the plastic deformation stage. Grain boundary reverted austenite had negligible influence on tensile strength and static toughness in the elastic stage, but was detrimental to static toughness during plastic deformation.

Keywords: T250 maraging steel, laser welded joint, strength and toughness, welding-aging treatment, static toughness, Ni_3(Ti, Mo) particles, reverted austenite

Introduction

T250 maraging steel is a high-strength, high-toughness steel developed from C250 cobalt-bearing maraging steel by eliminating cobalt and increasing titanium content [1]. Based on a carbon-free or micro-carbon martensitic matrix, the addition of Ti, Mo, and Al elements to a ductile Fe-Ni martensitic alloy enables significant strengthening through precipitation of intermetallic compounds during tempering or aging, substantially improving both strength and toughness [2-5]. Since T250 offers comparable high strength and toughness to C250 while eliminating costly cobalt, it has been widely applied in advanced aerospace technologies such as solid rocket motor casings. Welding is a key enabling technology for T250 steel applications [6-9].

Maraging steels are typically used in the aged condition, and welded structures fall into two main categories. The first comprises large precision components that require pre-weld aging to maintain dimensional accuracy during machining. The second includes smaller, more complex structures supplied in the solution-treated condition for ease of machining, followed by post-weld aging of the entire assembly [10]. Current welding methods for maraging steels primarily include tungsten inert gas welding, plasma arc welding, and electron beam welding. However, due to issues such as large heat-affected zones, microsegregation, and welding defects, neither pre-weld nor post-weld aging has achieved satisfactory matching of strength and toughness. Low strength and poor toughness remain persistent challenges in maraging steel welding [11-14]. Laser welding offers potential advantages for maraging steels due to its high energy density and low heat input. Compared with electron beam welding, laser welding involves lower equipment costs and eliminates the need for workpiece demagnetization. However, research on laser welding of cobalt-free maraging steels remains limited, and the effects of laser welding and aging processes on joint strength and toughness are not well understood [15-17].

This study investigates fiber laser welding of T250 maraging steel, focusing on two typical processing routes: pre-weld aging and post-weld aging. By varying the welding-aging sequence, we examine the strength and toughness of hybrid-treated joints and their influencing factors, providing guidance for further improvement of joint performance.

Experimental Methods

The base material was 2 mm thick T250 maraging steel plate in the solution-treated condition, with a chemical composition (mass fraction, %) of: Ni 19.0, Mo 3.0, Ti 1.5, Al 0.1, Cr 0.3, C 0.007, Si 0.03, S 0.002, P 0.005, Fe balance. The laser welding system consisted of a 2 kW IPG fiber laser (wavelength 1.07 μm, focused spot diameter 0.13 mm) and a four-axis CNC machine. Steel plates were cut into 50 mm × 50 mm × 2 mm specimens for laser remelting welding. The welding configuration is shown in [FIGURE:1]. Argon shielding gas was applied to both top and bottom surfaces at a flow rate of 25 L/min. Optimized welding parameters of 2000 W laser power and 3 m/min welding speed were used to ensure full penetration and high efficiency. Two hybrid treatment conditions were investigated: aging before welding and aging after welding. Aged base metal was obtained by solution-treated base metal subjected to the same aging treatment (480 °C for 3 h, air cooled).

Microstructures of base metals and hybrid-treated joints were examined using a BX51M/DP72 optical microscope (OM) and a JSM-7001F scanning electron microscope (SEM). Backscattered electron (BSE) imaging was performed on weld zones. Micro-area chemical compositions were analyzed using a JXA-8230 electron probe microanalyzer (EPMA). Microhardness across weld joints was measured with an FM-800 microhardness tester using a 300 g load and 15 s dwell time.

Tensile tests were conducted on base metals and welded joints (with reinforcement removed) using an auxiliary device on a Gleeble 1500D thermomechanical simulator to obtain stress-strain curves. Tensile specimen dimensions are shown in [FIGURE:2]. Joint strength and toughness were characterized by tensile strength (σb) *and static toughness* (U{OT}). Static toughness was calculated as the area under the stress-strain curve [18-21] using Matlab. Elastic deformation (d_1) and plastic deformation (d_2) were extracted from the curves to calculate static toughness during elastic (U_1) and plastic (U_2) deformation stages. All reported values represent averages of three specimens.

Results and Discussion

2.1 Tensile Test Results

Table 1 summarizes the tensile properties and static toughness of base metals and hybrid-treated joints. Significant differences exist among the various conditions. The solution-treated base metal exhibited the lowest tensile strength but highest static toughness. The aged base metal showed the highest tensile strength with relatively high static toughness. Both hybrid-treated joints fractured in the weld metal. The pre-weld aged joint had a tensile strength of 1016.5 MPa and static toughness of only 19.7 MJ/m^3. In contrast, the post-weld aged joint achieved 1618.2 MPa tensile strength and 49.6 MJ/m^3 static toughness.

These results demonstrate that pre-weld aging produces poor joint strength and toughness, with values of only 62% and 28% of the aged base metal, respectively. This indicates that the welding thermal cycle degrades the pre-aged microstructure, partially destroying the aging effect and representing the key factor limiting joint performance. Post-weld aging yields much better results, achieving 98% of the aged base metal’ s tensile strength and 71% of its static toughness. The tensile strength of post-weld aged joints significantly exceeds that of joints welded in the solution-treated condition, while static toughness values are comparable. Since solution-treated base metal welded joints exhibit similar strength and toughness to the solution-treated base metal itself, the fiber laser welding thermal cycle has minimal detrimental effect on the solution-treated condition. Thus, post-weld aging is the critical factor enabling superior joint performance.

Microstructure and Phase Analysis

Both hybrid-treated joints fractured in the weld metal, indicating that the weld zone is the weak link. Therefore, understanding the differences in joint strength requires detailed analysis of weld metal microstructure and phase characteristics. Figures 3 [FIGURE:3] and 4 [FIGURE:4] show OM and SEM images of base metals and weld metals under different conditions.

The solution-treated base metal consisted of lath martensite (Fig. 3a) with no precipitates observed in the martensite matrix or grain boundaries (Fig. 4b), resulting in low strength but excellent toughness. After aging, the lath martensite morphology was retained (Fig. 3b), but numerous dispersed precipitates approximately 50 nm in diameter appeared within the martensite matrix and prior austenite grain boundaries (Fig. 4d). These precipitates are identified as Ni_3(Ti, Mo) [22-24], which substantially increase strength while reducing toughness (Table 1).

When aged base metal was welded, the thermal cycle dissolved these precipitates completely into austenite, which then failed to precipitate during rapid cooling. Consequently, the weld metal contained no Ni_3(Ti, Mo) particles (Fig. 4f), resulting in significantly lower strength than the aged base metal. Due to rapid cooling during laser welding, the weld grain size was notably finer than in the solution-treated condition (Fig. 3a), contributing to higher strength than the solution-treated base metal.

Welding of solution-treated base metal produced a columnar weld microstructure with refined grains (Fig. 3d) and no Ni_3(Ti, Mo) precipitates (Fig. 4h), indicating minimal effect of the laser welding thermal cycle on the solution-treated microstructure. Consequently, its strength and static toughness were similar to the solution-treated base metal (Table 1). However, post-weld aging of this joint led to extensive precipitation of fine Ni_3(Ti, Mo) particles within the martensite matrix (Fig. 4j), beneficial for weld metal strength. Unlike aged base metal, post-weld aged joints exhibited light-colored dendritic structures along martensite grain boundaries (Figs. 3e and 4i), likely responsible for the slightly lower strength compared to aged base metal.

Figure 5 [FIGURE:5] shows BSE images of the post-weld aged joint weld zone, revealing significant segregation of Ni, Mo, and Ti at grain boundaries. EPMA quantitative analysis (Table 2) confirms no notable elemental segregation in solution-treated or aged base metals, but all welded joints show slight segregation of Ni, Mo, and Ti at weld grain boundaries. This results from the rapid heating and cooling cycle, which prevents diffusion of these elements, causing them to accumulate at the final solidification boundaries. This segregation lowers the reversion temperature for austenite formation [25], enabling austenite reversion at the aging temperature of 480 °C and precipitation along grain

Figure 8

Figure 1: Figure 8

boundaries. Therefore, the light dendritic structures in aged welds are reverted austenite, a relatively soft phase that reduces weld metal strength.

In summary, Ni_3(Ti, Mo) precipitates significantly enhance joint strength, while reverted austenite reduces it. In pre-weld aged joints, the welding thermal cycle eliminated Ni_3(Ti, Mo) precipitates, and although elemental segregation occurred, no reverted austenite formed. In post-weld aged joints, Ni_3(Ti, Mo) precipitates formed in the weld, but post-weld aging not only failed to eliminate the segregation-induced Ni, Ti, Mo enrichment at grain boundaries but also promoted reverted austenite formation. These microstructural differences result in post-weld aged joints having strength slightly below that of aged base metal but far exceeding that of pre-weld aged joints.

2.3 Factors Influencing Weld Joint Toughness

The different static toughness values of pre-weld and post-weld aged joints may stem from either the hybrid treatment sequence or the inherent heterogeneity of welded joints. Analysis of individual zones is therefore necessary. Figure 6 [FIGURE:6] shows cross-sectional OM images of hybrid-treated joints, revealing distinct corrosion characteristics and macrostructures among the weld metal (WM), heat-affected zone (HAZ), and base metal (BM). A partially melted zone (PMZ) exists at the weld edge, and a deeply eroded region (DER) with coarse grains appears 0.6-1.0 mm from the weld center.

Microhardness measurements (Fig. 7 [FIGURE:7]) show that both hybrid-treated joints exhibit softening in the HAZ, with average hardness values of 560 HV and 565 HV, respectively. SEM examination of HAZ regions (Fig. 8

) reveals that both conditions contain martensite matrix with dispersed Ni_3(Ti, Mo) precipitates in the PMZ (Figs. 8a and c) and light-colored reverted austenite particles in the DER (Figs. 8b and d) [26], indicating identical HAZ microstructures. However, weld metal hardness is the lowest among all zones, with pre-weld aged joints showing even lower values, and the weld microstructures differ significantly between the two conditions (Fig. 3). Therefore, toughness differences arise not from HAZ softening but from weld metal microstructural variations.

The pre-weld aged joint exhibited U_1 = 8.1 MJ/m^3 and U_2 = 11.6 MJ/m^3, while the post-weld aged joint showed U_1 = 25.7 MJ/m^3 and U_2 = 23.9 MJ/m^3 (Table 1). Thus, static toughness in both elastic and plastic stages is lower for pre-weld aged joints. Fracture surface SEM images (Fig. 9

) reveal large, shallow dimples in pre-weld aged joints (Fig. 9c) and small, deep dimples in post-weld aged joints (Fig. 9d). Microstructural analysis shows pre-

Figure 9

Figure 2: Figure 9

weld aged weld metal consists of columnar martensite (Figs. 4e and f), while post-weld aged weld metal comprises columnar martensite, dispersed Ni_3(Ti, Mo) precipitates, and grain boundary reverted austenite (Figs. 4i and j). Therefore, Ni_3(Ti, Mo) precipitates and grain boundary reverted austenite are key factors causing toughness differences.

Aged base metal shows higher U_1 but lower U_2 than solution-treated base metal (Table 1), with the primary microstructural difference being Ni_3(Ti, Mo) precipitates in the aged condition (Figs. 4b and d). These precipitates significantly increase tensile strength (σ_b) and elastic deformation (d_1), enhancing elastic stage static toughness (U_1). However, during plastic deformation, deformation incompatibility between precipitates and martensite matrix promotes crack initiation and propagation at precipitate sites, reducing plastic deformation (d_2) and plastic stage static toughness (U_2). Fracture morphology comparison (Figs. 9a and b) confirms that aged base metal exhibits smaller, shallower dimples than solution-treated base metal, verifying that Ni_3(Ti, Mo) precipitates provide additional crack sources during plastic deformation, accelerating fracture and reducing d_2.

Post-weld aged joints show similar U_1 to aged base metal but significantly lower U_2 (23.9 vs. 43.4 MJ/m^3, Table 1). The key microstructural difference is the presence of reverted austenite in the weld. Since post-weld aged joints have comparable σ_b and d_1 to aged base metal, reverted austenite has minimal effect on elastic stage properties and U_1. However, during plastic deformation, cracks readily initiate and propagate in reverted austenite, reducing plastic deformation (d_2) and plastic stage static toughness (U_2). Fracture surface comparison (Figs. 9b and d) shows post-weld aged joints have even smaller, shallower dimples than aged base metal, confirming that reverted austenite provides additional crack initiation sites, accelerating fracture and reducing d_2.

In summary, Ni_3(Ti, Mo) precipitates in post-weld aged joints enhance tensile strength and elastic deformation, thereby increasing U_1, but reduce plastic deformation. Reverted austenite has negligible effect on strength and elastic deformation but significantly reduces plastic deformation. Compared with preweld aged joints, post-weld aged joints contain Ni_3(Ti, Mo) precipitates that increase σ_b and d_1, resulting in higher U_1. Although both Ni_3(Ti, Mo) precipitates and reverted austenite reduce plastic deformation (d_2), the substantial strength increase from precipitates enables greater energy absorption during plastic deformation, yielding higher U_2 than pre-weld aged joints.

Conclusions

(1) Post-weld aging produces superior strength and toughness compared with pre-weld aging in T250 maraging steel. The weld zone is the critical region controlling joint performance. Dispersion of fine Ni_3(Ti, Mo) precipitates in the weld metal is the fundamental reason for the superior properties of post-weld aged joints.

(2) Ni_3(Ti, Mo) precipitates increase tensile strength and elastic deformation, benefiting elastic stage static toughness. These precipitates have a dual effect on plastic stage static toughness: they increase strength but reduce plastic deformation.

(3) Grain boundary reverted austenite has negligible influence on tensile strength and elastic deformation, thus minimal effect on elastic stage static toughness, but significantly reduces plastic deformation and plastic stage static toughness.

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Figure 11

Figure 3: Figure 11

Figure 13

Figure 4: Figure 13

Figures

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Figure 18

Figure 5: Figure 18

Figure 19

Figure 6: Figure 19