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Laser Beam Welding Tempered 300M Ultrahigh Mechanical Strength Steel

AISI 300M ultrahigh strength steel has been used in a number of high demanding applications, such as the VLS Brazilian rocket project. This work intends to propose laser beam welding, with subsequent tempering, as a possible route for the fabrication of engineering pieces of this steel. A 2 kW fiber laser was used to produce welded coupons for metallographic, hardness and tensile strength tests. It has been shown that convenient laser parameters for a 3 mm thick plate are 50 mm/s welding speed and 1200 W laser power. However, both welded materials and heat-affected zones presented high hardness and negligible plastic deformation. In order to produce useful engineering parts, it was suggested a tempering treatment for 2 hours at temperatures of 200 or 400°C. Tensile mechanical testing has shown that welded and tempered coupons presented both yield and maximum strengths comparable to the unwelded material. On the other hand, a maximum elongation of about 4% was obtained, in comparison with 12% from the bulk sample.

Keywords: AISI 300M steel, tempering, heat treatment, laser beam welding

Introduction

The ultrahigh mechanical strength class of steels (UHSS) is quite broad and includes several distinctly different families of steels such as medium-carbon low-alloy steels, medium-alloy air-hardening steels, high fracture toughness steels and maraging steels (ASM, 1993). The medium-carbon low-alloy family of ultrahigh-strength steels includes AISI/SAE 4130, the high-strength 4140, and the deeper hardening, high-strength 4340. Several modifications of the basic 4340 steel have been developed. In one modification, silicon content is increased to prevent embrittlement when the steel is tempered at the low temperatures required for very high strength, giving rise to the 300M steel. The Brazilian satellite launcher rocket VLS extensively uses 300M steel for the solid propellant stages. Three of four thrusters are made of 300M while one is made of a composite structure (Bosco et al., 1985).

The 300M steel presents elevated hardenability with good ductility and toughness and ultimate strength typically between 1860 and 2070 MPa (ASM, 1993). Typical heat treatments for 300M steels are normalizing, hardening and tempering. Normalizing usually is carried out between 915 and 940°C for a period depending on the part dimensions followed by air-cooling. Hardening is obtained by austenitizing in temperatures between 860 and 885°C followed by quenching in oil or salt bath. Tempering is obtained by maintaining the pieces at temperatures between 260 and 315°C for 2 to 4 hours, in order to obtain a good combination between high yield strength and good toughness (ASM, 1993). Since the 300M steel is easily hardenable, tempering is an obligatory step in manufacturing since most mechanical properties could be tuned by tempering temperature and residence time.

Anazawa et al. (2006) verified that AISI 300M steel evolves during aging at ambient temperature due to the transformation induced plasticity (TRIP) mechanism. This effect is linked to a continuous transformation from austenite to martensite with benefits to plastic deformation, maintaining high tensile strength levels (Anazawa, 2008).

Lee and Su (1999) studied microstructure and mechanical properties of quenched AISI 4340 steel, similar to AISI 300M, under different tempering conditions. These authors had used samples provided in the form of extruded bar, austenitized at 850°C for 30 minutes, cooled in oil, and made a subsequent tempering in temperatures between 100 and 650°C for 2 hours. The mechanical properties obtained by these authors are presented in Table 1.

Table 1. Mechanical properties of AISI 4340 steel after tempering for 2 h at different temperatures (Lee and Su, 1999). AQ = As Quenched.

Property	Tempering temperature (°C)							
	100	200	250	300	400	500	650	AQ
Yield strength (MPa)	1828	1627	1528	1436	1300	1110	814	2115
Tensile strength limit (MPa)	1997	1792	1696	1587	1437	1294	977	2214
Vickers hardness (HV)	617	536	497	486	460	407	356	660
Reduction of area (%)	40.0	41.0	42.0	35.0	45.0	50.0	57.0	33.7
Elongation (%)	8.4	8.6	9.8	8.8	10.0	14.0	18.1	4.5
Strain hardening coefficient	0.53	0.5	0.48	0.42	0.38	0.32	0.21	0.57

Lee and Su (1999) results showed that as-quenched condition creates martensite that is responsible for high yield strength and high hardness values, but with low elongation. Tempering had been used to produce a more ductile bar and a convenient balance between mechanical strength and elongation could be tuned by an appropriate heat treatment (Table 1).

Welding usually produces effects similar to quench in the resolidified and heat-affect regions, such as high yield strength, high hardness and low elongation levels, due to martensite formation. AISI 4340 and 300M steels are suitable for welding only when they are in the annealed or normalized condition (Key to Metals, 2010). After welding, they have to be heat treated to obtain the desired balance of properties. The gas tungsten arc, the gas metal arc, the shielded metal arc, and the gas welding process are all used for welding these steels. The composition of the filler metal when required is designed to produce a weld deposit that responds to a heat treatment in approximately the same manner as the base metal (Key to Metals, 2010).

Although of important applications in the aerospace industry, the ultrahigh strength steels welding, in particular 4340 and 300M classes, is very poorly documented in the literature. Roshangias et al. (2010) studied gas tungsten arc welding characteristics of 35NiCrMoV123 ultrahigh strength steel showing that a post welding heat treatment at 310°C produces a convenient impact resistant structure composed of lower bainite. Mujica et al. (2009) studied laser beam welded TWIP (Twinning Induced Plasticity) steels which are able to reach elongations up to 0.6 true strain and tensile strengths of up to 1200 MPa true stress. These authors have shown that refined austenite grains were obtained in the fusion zone, leading to a local increase on fracture toughness due to the

strengthening mechanism. Daneshpour et al. (2009) realized a study about laser and spot welding on high strength steel DP780 on fatigue conditions. These authors have shown that fatigue strength of the laser welds is as good as or even better than that of the resistance spot welds. This fact reveals that laser welds on DP780 steel can be a viable alternative to the conventional resistance spot welds.

Even though the Institute of Aeronautics and Space/Brazil has been working on arc and plasma welding of 300M steel for many years (IAE, 2011), it is now time to move forward to prove the usefulness of laser beam welding to reduce both weld and heat-affected zones widths. The objective of this contribution is to study the feasibility to produce sound joints of the AISI 300M steel using a high-power laser system and to determine the subsequent heat treatment for engineering uses.

Material and Methodology

The steel used here is an AISI 300M grade produced by Eletrometal Açõs Finos SA and its chemical composition is given in Table 2 (Fe balance). The material was furnished as 3-mm thick sheets in normalizing condition (900°C / 1 hour / furnace cooled to ambient temperature).

Table 2. Chemical composition of the steel (wt.%).

Elements	%
C	0.39
S	0.0005
P	0.009
Si	1.78
Mn	0.76
Cr	0.76
Ni	1.69
Mo	0.40
Al	0.003
V	0.08
Cu	0.14

A 2 kW continuous wave fiber laser produced by IPG Co. was used here. The laser radiation is generated in 50 µm diameter fiber doped with ytterbium. The doped fiber is connected to a process fiber with 100 µm diameter and 10 m long, which is then connected to an Optoskand processing head. The focal length was 157 mm with a minimum spot diameter of 100 µm.

Pure argon gas at 30 l/min flow rate has been used to protect the surface against oxidation. The protection gas was delivered through a rounded copper tube of 3 mm internal diameter directly over the irradiated area. The samples moving are realized by a CNC table with a constant velocity ranging from 1 to 160 mm/s. Just before welding the sample surface was grounded with a SiC 600 paper to remove oxidation and then washed with ethanol.

Microstructural analyses were carried out using Optical Microscopy (OM), Scanning Electron Microscopy (SEM) and Microhardness Testing (HV). The optical microscope is a reflected light Reichert Polyvar 2 equipped with acquisition system and image processing software. The scanning electron microscopy is a Zeiss Model LEO 435 Vpi and it was used to study fresh fractured surfaces. The microhardness tester is a Future-tech FM 700 equipment using a Vickers pyramid and loads from 5 to 500 gf. Here, the applied load was 200 gf and the application time was 9 s. The furnace used to heat treatments is an electric Fornitec brand. All heat treatments were carried out after the furnace has stabilized its temperature for at least 6 hours. Tempering was realized in normal

atmosphere and cooling was carried out by putting the samples out of the furnace on a ceramic brick.

The equipment for mechanical tests was an MTS 810 tensile machine, with a load cell with a capacity of 250 kN. The speed of displacement of the head was 1.0 mm/min. For each welding condition, three samples were tested in tension with the welding direction perpendicular to the tensile direction. For the current mechanical tests the applicable standard was ASTM E8M-95a (ASTM, 1995). Following the standard, the tensile testing sample had 3 mm thickness and 10 mm nominal width for a total length of 100 mm. The reduced area had 32 mm length and 6 mm width.

Results and Discussion

Laser Beam Welding (LBW)

The two most important process parameters for LBW are the laser speed and power, which were changed accordingly to the photos in Figs. 1 and 2. The parameters are around the 800 W power and 50 mm/s speed since these values represent typical steels welding in the lab. The other parameters were constant: argon flux 30 l/min over the weld pool; cross-jet gas protection of N₂ for the optics; 5° laser inclination with respect to the surface, to avoid back reflection into the cavity and focus on the materials surface and all welds are bead-on-plate. Figures 1 and 2 present an optical micrograph of the transversal cross-section for each condition, for comparison. The scale bar in each photo represents 0.5 mm.

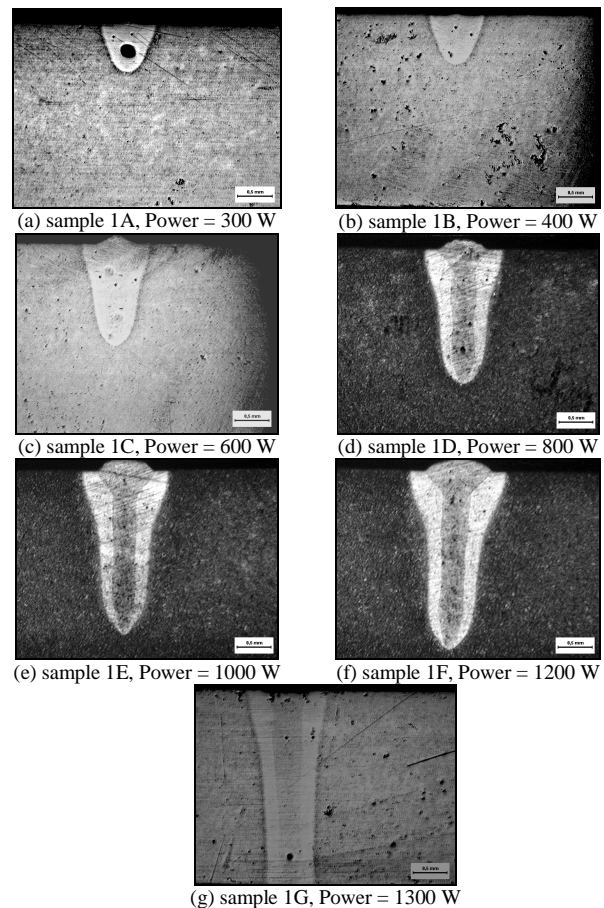


Figure 1. Micrograph of cross-section weld beads ($v = 50$ mm/s).

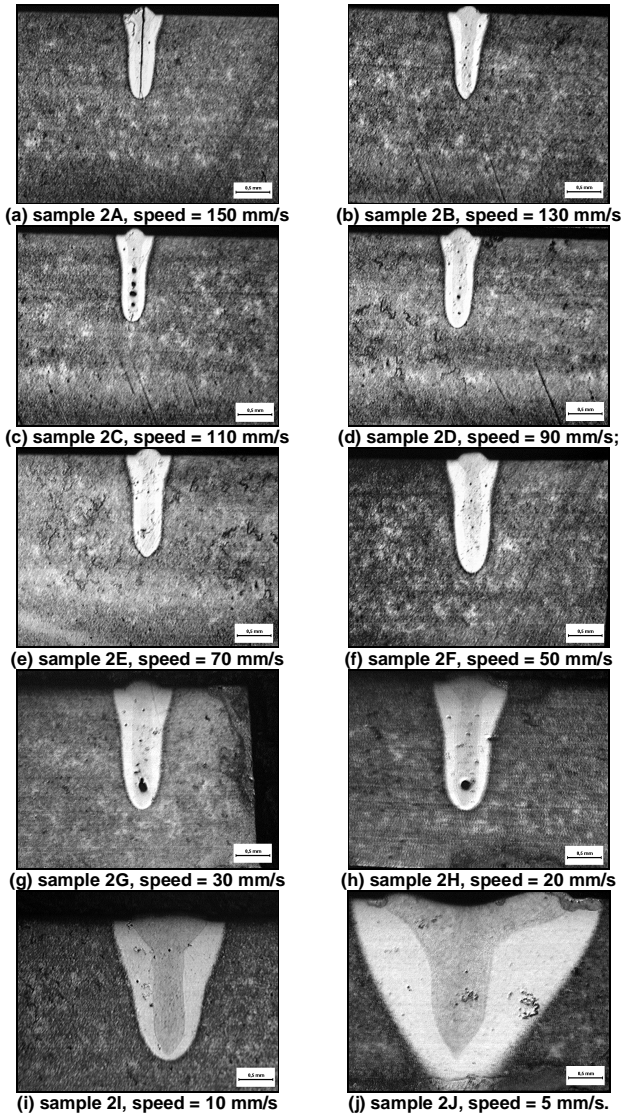


Figure 2. Laser beam welding parameters and related cross-section weld beads ($P = 800$ W).

Some porosity is verified in the micrographs of Fig. 1 and Fig. 2, due to the degassing of the base material. In some cases, such as 2C, it is clearly observed that porosity segregates to the centreline of the weld were the melt solidifies at last. A centreline alignment of porosities is a problematic situation in welds because causes a weak joint, ready for cracking. Cracking is sometimes observed when the speed is too high, such as in 2A. At 150 mm/s, the cooling rate is so high that strain rate during welding (shrinkage plus rapid cooling effects) could cause cracking, particularly solidification cracking (Rappaz, 1999). From Fig. 1 and Fig. 2, it is clear that the melted zone (MZ) and heat-affected zone increase with increasing laser power and decreasing weld speed. Welding at very low speeds (eg. Condition 2J) results in a large heat-affected zone (HAZ) somewhat similar to arc welding aspect. The effect of both parameters on weld depth could be also seen in Fig. 3. The influence of speed on the weld depth is approximately inverse power function and power versus depth is approximately linear. As the heat input is usually the ratio between laser power and weld speed, the influence of the heat input in the melt depth is almost ascendant linear.

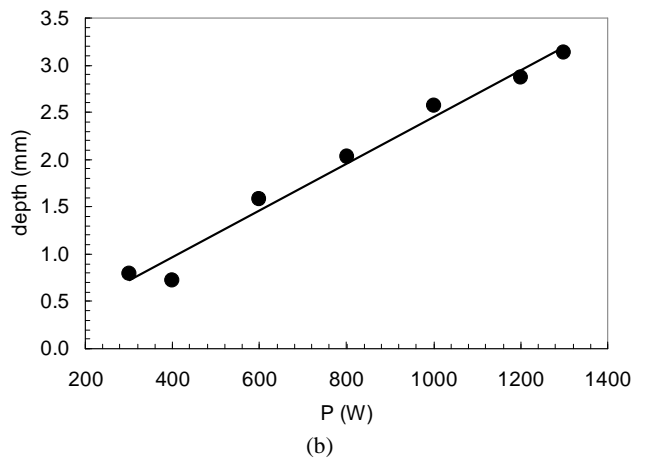
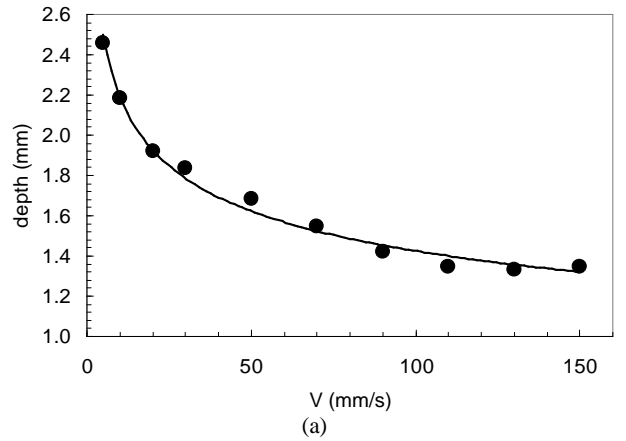


Figure 3. Effect of (a) laser power and (b) weld speed on welding depth.

Figure 4 presents the results of Vickers Hardness (HV) testing for each experimental condition in the melted zone (MZ, dark gray bars) and heat-affected zone (HAZ, light gray bars). As could be seen, the hardness did not change significantly from sample to sample, being around 670 HV for both zones. This value represents an increase of 55% compared to the base material hardness (horizontal line in Fig. 4). This high hardness value results from the martensite structure (Fig. 5) produced in both MZ and HAZ.

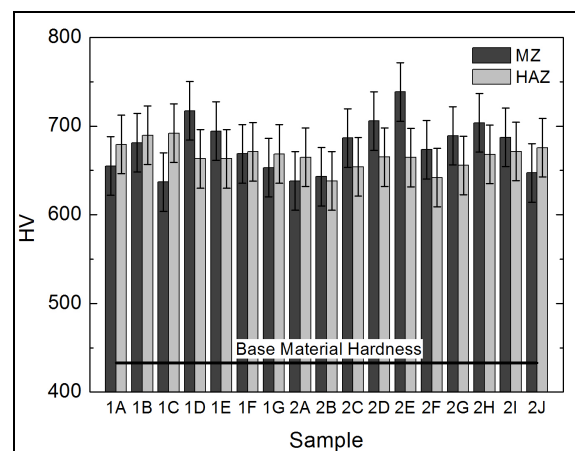


Figure 4. Results of Vickers Hardness for each experimental condition.

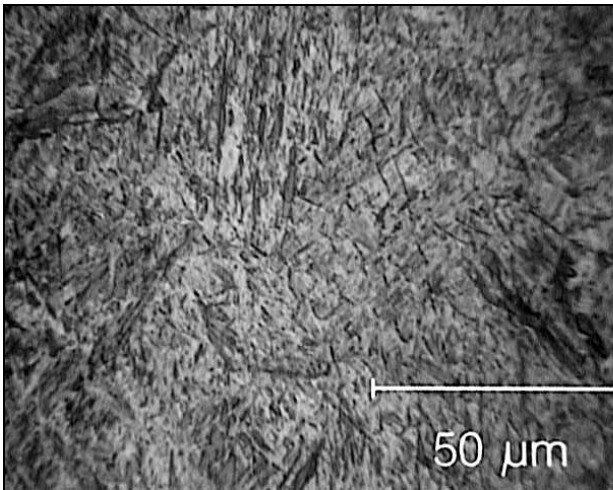


Figure 5. Martensitic structure observed in the melted zone of the sample 1F.

The condition where it is observed a full penetration weld is 1F, which had been retained for the continuation of the study. The condition 1G also presented full penetration, but the root of the weld has shown dropout (liquid flow) due to the excessive power. Since the resulting microstructure in all studied conditions is mainly martensitic, the results obtained for sample 1F could be considered as well as for the other conditions.

Tempering

A 3 mm thick sheet was welded at 1200 W laser power and 50 mm/s weld speed and then sectioned in coupons for tempering. Tempering was carried out as proposed by Lee and Su (1999) within the temperature interval 100 to 650°C during two hours. The tempering temperatures were: 100, 200, 250, 300, 400, 500 and 650°C.

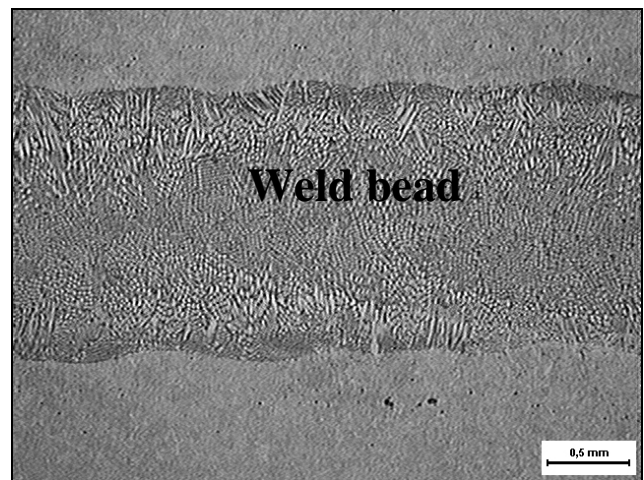
It must be pointed out that MZ and HAZ, mainly composed of martensite, passed by the first tempering while the unaffected bulk material experienced an additional heat treatment.

The microstructural evolution for the tempered coupons had shown carbides growth in both MZ and HAZ. Carbides in HAZ decorated both the grains and the grain boundaries and in MZ darkened the interdendritic regions. Figure 6 shows the micrographs of the polished and etched surface of the welds after tempering at 200°C. Figure 6a shows that MZ is composed by dendrites of gamma phase, which could be seen with more details in Fig. 6b. Heat-affected zone (HAZ, in Fig. 6b) is finely decorated with tempered martensite. The region between MZ and HAZ presents well marked grain boundaries as a result of liquation (Kou, 2003).

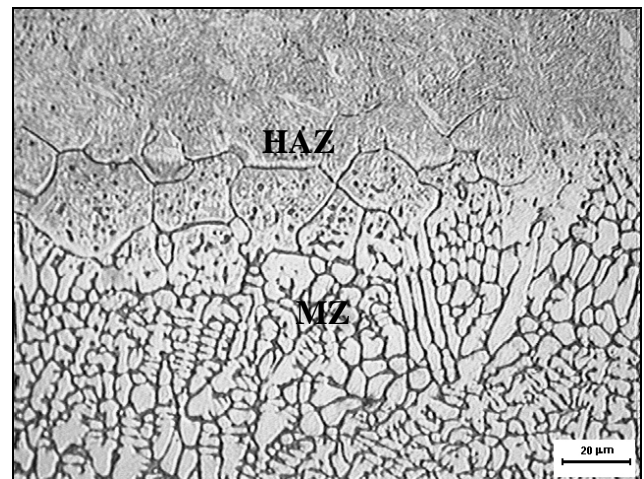
Hardness tests of the tempered coupons were compared with those realized by Lee and Su (1999) in AISI 4340 steel, as can be seen in Fig. 7. The results are quite similar, even considering the different steel compositions, AISI 4340 and 300M, and different processing routes: quenching and laser beam welding. The trend line equation for this work is $HV = 641 - 0.5052 \times T$, compared to $643 - 0.4694 \times T$ of the literature data (Lee, 1999). Base material hardness was approximately constant up to 500°C and then dropped because of austenite grain growth.

From Fig. 7 it can be seen that hardness maintained high values in temperatures below 200°C. Above 500°C both welded and base material became too soft. Additionally, from Lee and Su (1999) studies, carbide films form around the retained austenite grains around 300°C, with associated loss of materials toughness.

Therefore, for continuation of the work, the tempering temperatures of 200 and 400°C were chosen.



(a)



(b)

Figure 6. Top surface micrographs of weld after tempering at 200°C.

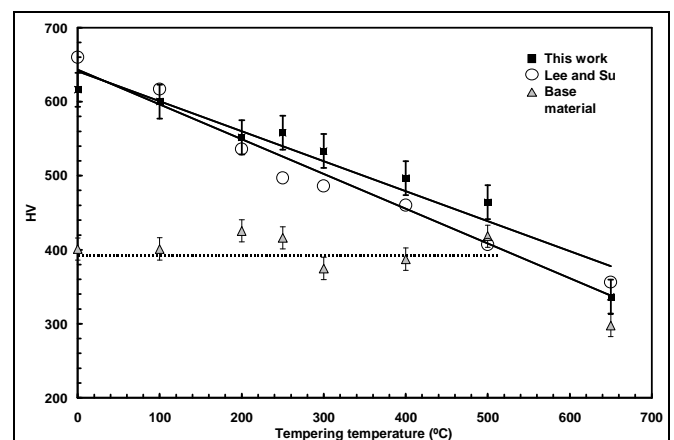


Figure 7. Hardness values after tempering obtained in this work in comparison with reference Lee (1999) and with the base material.

Tensile Strength Testing

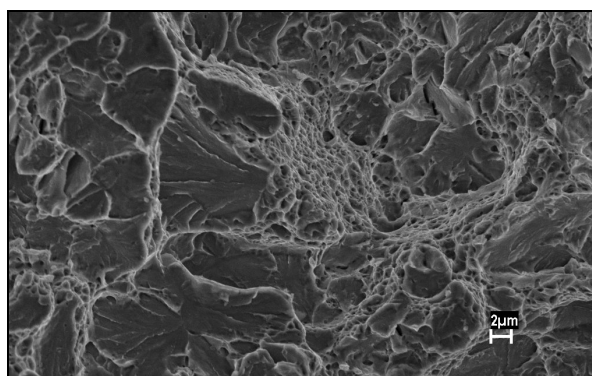
Tensile strength testing was carried out in three coupons each at conditions given in Table 3. Three bulk specimens, without welding, were also tested for comparison. The results are presented in Table 3.

Table 3. Conditions for tensile strength tests and summary of the results.

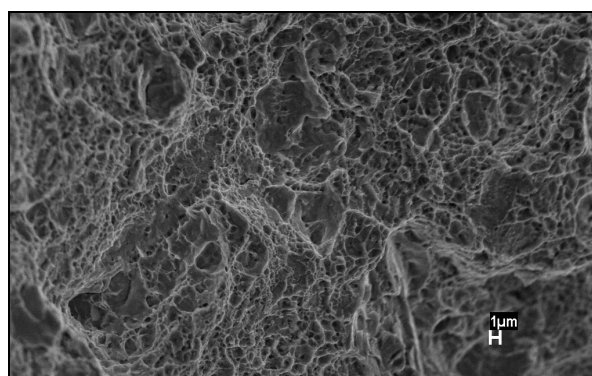
Condition	Bulk	As-welded	Welded-200	Welded-400
Welding	No	1200 W, 50 mm/s	1200 W, 50 mm/s	1200 W, 50 mm/s
Tempering temp. (°C)	No	No	200	400
Yield strength (MPa)	925 ± 67	*	1028 ± 122	1150 ± 10
Tensile strength (MPa)	1611 ± 65	592 ± 87	1555 ± 239	1295 ± 75
Elongation (%)	12.0 ± 0.3	0.9 ± 0.7	4.0 ± 1.9	4.7 ± 2.0
Reduction in area (%)	18 ± 8	**	1.3 ± 0.2	6 ± 5

* Could not be measured. ** Negligible.

The bulk specimen reached the high values of yield and maximum strength, elongation and reduction in area after breaking, being considered the standard optimum values. As-welded sample has shown very poor mechanical properties with insignificant plastic deformation, showing the importance of subsequent tempering treatment.



(a)



(b)

Figure 8. Micrographs of the fractured surfaces after tensile tests: (a) as-welded and (b) welded and tempered at 200°C.

The coupons submitted to tempering recovered the tensile strength level of Bulk sample, but with losses in the plastic deformation behavior, reaching about 1/3 of the elongation observed in the solid material. Nevertheless, considering the welding restrictions, these coupons welded and tempered present convenient properties for further studies aiming applications in mechanical construction.

Two micrographs in Fig. 8 present the fractured surfaces for as-welded (a) and tempered at 200°C (b) conditions. As can be seen, the as-welded condition presents a mixed mode fracture with cleavage and dimples characteristics of a material with limited ductility. On the other hand, the tempered sample (Fig. 8b) presents a fractography composed by dimples showing more ductile failure behaviour.

Conclusions

After analyzing the results, the following conclusions could be drawn:

- The welding depth is dependent on the laser power and weld speed, attaining the maximum depth for the AISI 300M steel sheet (3 mm) at 1200 W and 50 mm/s.
- The weld bead presented high hardness in all experimental conditions. The melted zone and heat-affected zone had an average hardness of 670 HV, with martensite formation throughout. The as-welded condition also presented a negligible elongation with very poor tensile mechanical properties.
- Hence tempering was studied in a range of temperatures between 100 and 650°C with residence time of two hours. Two different tempering temperatures were chosen, 200 and 400°C, where the hardness has decreased without affecting the bulk material. Tensile mechanical test of welded and tempered coupons has shown good yield and maximum strength values, but with some losses on ductility.

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