An Analysis of the Mechanical Behavior of AISI 4130 Steel after TIG and Laser welding process.

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Abstract

Metallic materials have received special attention in the aerospace and defense areas. A few decades ago, Brazil was faced with technological challenges concerning the production and processing of ultra-high strength steels, such as AISI 4340 and SAE 300M steels. The AISI 4130 steel had been also considered, since it is applied in landing gears, small aircraft engine cradles, and besides general industries. In this work, as a comparative welding process, Laser Beam Welding (LBW) was used as an alternative to the traditional TIG (Tungsten Inert Gas) welding. For the mechanical characterization of laser and TIG welds, tensile and hardness tests were performed. Microstructural characterization through optical microscopy was realized as well, in the fusion zone (FZ) and heat-affected zone (HAZ). Martensite was found in the fusion zone for both processes. However the average grain sizes were different due to different heating and cooling rates. In the present study, the weld was autogenous and a post weld heat treatment was conducted to evaluate its influence on mechanical properties. This treatment proved to improve the ductility of the steel and reducing the embrittlement in the welded region. It was observed that the thicknesses of the FZ and HAZ in the TIG welds were ten times larger than in the laser. The hardness values observed in FZ and HAZ were similar in both cases. Tensile strength after heat treatment remained at levels similar to the base material. After the heat treatment, there was a recover in the material ductility, particularly after the laser welding, demonstrating the usefulness of the process.

1. Introduction

Aerospace projects should take into account the difficulties of transporting a load against the gravity force during take-off and flight in an efficient way, with minimum cost and maximum safety, because failures in any of these stages might implicate in catastrophic accidents, involving human lives. Many components under extreme loads had been welded, so civilian and military aerospace companies are looking for better welding procedures [1, 2].
A few decades, Brazil was faced with technological challenges concerning the production and processing of ultra-high strength steels, such as AISI 4340 and SAE 300M, to reduce weight and improve mechanical properties at the weld beads. AISI 4130 steel had also been considered, since it is applied in landing gears, small aircrafts engine cradles, and also in the general-industry [1, 3 5].

The key applications to guide this study were landing gears and engine cradles. These are complex structures usually made of AISI 4130 tubes of several dimensions and welded by Tungsten Inert Gas (TIG) in different angles. In aeronautics, however, where the search for innovation is a paramount target, it is important to compare Laser Beam Welding (LBW) as an alternative to TIG welding.

In the present study, the welds were autogenous in both processes, TIG and laser. Mechanical behavior were evaluated in as-weld and heat treated condition in order to access the effect of tempering. During the welding process, the mechanical behavior of weld beads can change dramatically, so tempering may be beneficial, improving the ductility of the weldment and increase overall toughness.

2. Experimental

2.1. Material

Workpieces with 1.0 mm thickness were prepared for each test. The chemical composition for the AISI 4130 steel is shown in table 1 and Fig.01 present the base material microscopy.

![Fig.01: Base Material Microscopy](image)

| Elements   | C   | Mn  | P_{max} | S_{max} | Si  | Cr  | Mo |
|------------|-----|-----|---------|---------|-----|-----|----|
| AISI 4130  | 0.30| 0.60| 0.008   | 0.010   | 0.23| 0.80| 0.25|

2.2. Microscopy

Samples were cut and metallographically prepared through a sequence of grinded papers and then polished using alumina slurry. After polishing the samples were etched using a 2% Nital and 4% Picral chemical reagent and analyzed in an optical microscope (OM), Zeiss Axio Imager A2m, and a Hitachi Model TM-1000 Scanning Electron Microscope (SEM).
2.3. Welding Process

The laser parameters were previously studied according to Cardoso and Carvalho works [3, 5], which used the same laser.

The laser welding process was autogenous (no material addition) and was performed with a 2kW IPG Ytterbium Fiber Laser, Model YLR-2000, operating at 750W with a 0.1 spot size focused at the top of the weld surface. The travel speed was kept constant at 60 mm.s\(^{-1}\). Argon shielding protected the workpiece against oxidation.

TIG welding process was manually performed with a Miller XMT 304 CC/CV equipment, operating at continuous and polarized current. The operating parameters were speed of 1.65 mm.s\(^{-1}\), tension of 7.4 V, and current of 20A. Argon shielding protected the workpiece against oxidation. Table 2 summarizes the experimental conditions.

| Process | Power (W) | Speed (mm.s\(^{-1}\)) | Voltage (V) | Current (A) |
|---------|-----------|----------------------|-------------|-------------|
| Laser   | 750       | 60                   | --          | --          |
| TIG     | 148       | 1.65                 | 7.4         | 20          |

2.4. Heat Treatment

After the welding process, some of the specimens were subjected to tempering. This was performed in a furnace at a temperature of 400 °C for 2 hours.

2.5. Hardness Test

Hardness test measurements were performed on the Vickers scale (microhardness tester FM-700 Future Tech) with a load of 100 gf for 10 seconds. The measurements were performed in the transverse and longitudinal directions of the weld bead, covering the Base Material (BM), the heat affected zone (HAZ) and the Fusion Zone (FZ). For comparison the hardness tests were performed in the welded zone (TIG and laser) before and after the heat treatment.

2.6. Mechanical Test

The tensile testing was in accordance with ASTM E 8M standard, see Fig. 02, and performed with a Instron 338 universal equipment. The weld line was localized at the center of each workpiece. For comparison the measurements were performed in the welds (TIG and laser) before and after the heat treatment.

Fig. 02: Tensile Test work piece - (a) TIG and (b) Laser weld
3. Results and Discussions

3.1. Microscopy

For a better understanding of weld characteristics in both processes, images obtained with different magnifications were used:

a) Macroscopic to enable a visualization of the entire weld area and;

b) Microscopic to allow understanding of the details of the fusion zone and heat affected zone.

Fig.03 and Fig.04 show the welded regions in both cases, TIG and Laser, respectively. In Fig. 03(a), welded by the TIG process, it can be seen that the dark-gray region (fusion zone - FZ and heat affected zone - HAZ) is approximately ten times larger than the length of the laser weld, shown in Fig.04(a). For TIG welding, there is a slight bending of the plate and the separation between HAZ and FZ. However, in Fig. 04(a), showing the welding performed by the Laser process, there is a narrower welded region, showing different zones, the HAZ of darker shade, and FZ in the center with a lighter shade [6].

The SEM micrographs shown in Fig.03 (b) and Fig.04(b) shown the difference of the grains at the fusion zone. The observed difference in grain size in HAZ is caused by the different cooling times in the Laser, Fig. 04(c), and TIG, Fig. 03(c,d,e,f,g) processes. Laser cooling is faster because this process has more precise energy and fast speed, so the grains do not have the possibility of growing. The TIG process, on the other hand, has a slower cooling speed, generating a larger HAZ and several different grain sizes, which also appear larger.
Fig. 04 shows the formation of the martensitic phase in fusion zone region for both welding processes. The martensite presence is responsible for high hardness and brittleness. This phase is formed due to rapid cooling during welding, reaching the fusion phase, passing through the region of austenitizing and then by cooling after welding.

In TIG Fig 05 (b), welding heating and cooling is slower, resulting in a larger grain size in FZ and HAZ nearby, Fig 03(c). In the Laser process, Fig.05(a), faster heating and cooling generate smaller grains in this region and HAZ, Fig 04(c). Also, the lighter shaded regions, indicate, the possible formation of retained austenite, as observed in the related literature [7].

Fig. 05: Optical Microscopy showing the martensitic microstructure present in the Fusion Zone: (a) Laser Welding, (b) TIG Welding – 2% Nital
3.2. Hardness Tests

Vickers hardness tests were performed on the welded samples in order to evaluate changes in hardness along the FZ, the HAZ and BM, with and without heat tempering. The hardness results are shown in the graphs of Fig. 06(a) and 06(b).

Fig.05 (a), showing hardness results for both welding processes without tempering, there is a significant increase in hardness along the weld bead in the fusion zone because of the high cooling rate. The increase in hardness value from 250 HV average found on the base material rose to about 650 HV on laser welding; and 600 HV using TIG welding, indicating that there was the formation of a hard phase in FZ, with hardness values compatible with the martensite phase [8].

The graph of Fig. 06(b) after tempering, shows the action of the heat treatment, reducing the average values of hardness FZ 650 HV to 450 HV, for laser welding and 600 HV to 500 HV, for TIG welding.

![Hardness measurements](image1)
![Hardness measurements](image2)

Fig. 06: Hardness measurements after welding processes by Laser and TIG: (a) measures after welding without application of tempering, (b) measures after heat treatment of tempering.

After tempering it was observed a reduction of the martensite hardness at the welded region. This process is important because it reduces the difference between the values of welded region hardness and the phases at the base material (ferrite and pearlite), improving toughness during mechanical loading. Comparing to Wang et al., the hardness is compatible but the process was EB (Electron Beam) [9].

3.3. Tensile Test

The specimens were studied under the following conditions: as received (AR), material after welding by TIG or Laser process, with and without heat tempering. The graphs in Figs. 07 and 08 show curves obtained in tensile testing conditions for TIG, laser or BM (without welding), without or with tempering, respectively. The stress-strain curves had different behaviors for different conditions.

It is observed in the graph of Fig. 07 that the yield stress values and strength of the base material and both welded conditions are close. Ductility, however, as measured by deformation, is substantially reduced for both TIG and Laser welded specimens. This fact is related to the microstructural differences between the welded area and the base material. Plastic deformations are confined to the welded region and nearby. The presence of defects such as microcracks and pores can also contribute to reduction in plastic deformation of the steel before rupture.

The welding process act as a heat treatment, like a quenching. After welding, formation of martensite occurs, increasing the hardness and weakness. The weld has a small volume of material, compared to the non-welded area, so the high temperatures developed in the FZ fall faster after welding by heat extraction through the HAZ and BM, enabling the formation of martensite.
After the tempering, the material recovers part of its lost ductility after welding. This treatment produces a decrease in hardness of the phases, which is reflected in the increase in ductility, but with some reduction in strength, as can be seen in Fig. 08.

Partial ductility recovery (about 2%) was observed in the steel-welded by TIG process and a total recovery in the laser-welded steel. The tensile curve of laser welded material after tempering was very similar to the tempered base material behavior. These results show the benefit of tempering and laser welding superior quality as compared with that of TIG process.

Tab. 03 shows the results of tensile tests, with appropriate standard deviations. It is observed that there is little variation in yield strength ($\sigma_e$) and there is an increase in the amount of $\sigma_t$, for all conditions. Tempering, 2 hours - 400°C, also produced an aging effect on the base material. It is interesting to note that the main effect of tempering is to increase the ductility for the weld steels.

| Heat Treatment Pos Weld | Steel AISI 4130 | Yield strength $\sigma_e$ (MPa) | Ultimate strength $\sigma_t$ (MPa) | Maximum strain (%) |
|-------------------------|----------------|-------------------------------|-----------------------------------|--------------------|
| Without Tempering       | Laser          | 690 ± 10                      | 870 ± 40                          | 3.3.1. 10 ± 1      |
|                         | TIG            | 680 ± 60                      | 910 ± 70                          | 11.9 ± 0.3         |
|                         | BM             | 670 ± 7                       | 991 ± 4                           | 25.5 ± 0.1         |
| Tempered                | 3.3.2. Laser   | 3.3.3. 748 ± 6                | 3.3.4. 930 ± 9                    | 3.3.5. 13 ± 4      |
|                         | TIG            | 790 ± 60                      | 920 ± 40                          | 9.4 ± 0.4          |
|                         | BM             | 790 ± 50                      | 950 ± 20                          | 15.8 ± 0.6         |

4. Conclusions

The two welding processes used for 4130 steel sheets; Laser welding and TIG, proved to be viable, with little loss in mechanical properties.
The Laser welding process is faster, easily automated and produces area phase transformation area (Fusion Zone and Thermally Affected Zone) about ten times smaller than TIG welding process.

The hardness in the fusion zone is quite high for both processes, but it was reduced to about 200 HV for the laser welded steel and about 100 HV in TIG process after tempering.

The tempering applied after welding improved the ductility of the steel, transforming the martensite and enhance the compatibility between the phases. This effect was more noticeable in laser welding.

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