Hot cracking of Structural Steel during Laser Welding

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Abstract. Laser welding is an important technique in many industries due to its high precision in operation, its local and fast processing, narrow welds and its good weld surface quality. However, the process can involve some complications due to the rapid heating and cooling of the material processed, resulting in physical and metallurgical effects as thermal contraction during solidification, giving as a result the presence of residual stresses in the narrow weld. Formation of defects during the process is an important topic to be evaluated in order to achieve better performance of the steels in use. In the present work, defects formed during laser welding of a structural steel have been investigated. The defects formed have been identified and the causes of the defects are discussed. Possible strategies for improvement of the welding procedure and final weld result are proposed. The defects were analysed by optical and scanning electron microscopy and hardness measurement. Cracks were located in the middle of the fusion zone and followed both inter-granular and trans-granular paths. Impurities as manganese sulphides were found along the welding direction, and could act as sites for crack formation. The cracks formed during solidification of the weld are identified as solidification cracks. This kind of cracks is usually caused by solidification shrinkage and thermal contractions during the process, which appear in the fusion zone and sometimes in the heat affected zone.

1. Introduction

The laser welding process is considered important in different industrial applications due to its ability to achieve narrow welds and good weld surface quality. The process has high precision and it is a fast processing method. For many industries, control of the laser welding process has become a challenge in order to be able to produce uniform weld quality without affecting the mechanical properties of the material [1]. The demands to create high strength and high quality steels for automotive applications have increased by the years. With regard to the increased demands, defects formed during laser welding process are a very important topic to understand and control in order to produce welds with high strength and quality.

1.1. The laser welding process

The laser welding represents a delicate balance between heating and cooling within a spatially localized volume overlapping two or more solids, in such way that a liquid pool is formed and remains stable until solidified. The main goal of applying laser welding is to create the liquid melt pool by absorption of incident radiation, allow it to grow to the desired size, and then to propagate this melt
pool through the solid interface in order to join the two components together. Unsuccessful result is obtained if the melt pool is too large or too small or if significant vaporization occurs while it is present. The quality of the weld can be deteriorated by vaporization of alloy components, excessive thermal gradients that lead to cracking during solidification and instabilities in the volume and geometry of the weld pool that can result in porosity and void formation [2].

1.2. Crack formation mechanisms
Crack formation during the welding process can appear due to the rapid heating and cooling of the material processed, resulting in physical and metallurgical effects. When the material solidifies in the fusion zone, different complex phenomena occur and, both the fusion zone and the surrounding areas can be affected by thermal expansion and contraction, resulting in residual stresses in the narrow weld [3].

1.3. Metallurgical aspects
Different metallurgical factors can affect the quality of laser weld. These can be beneficial or detrimental for crack formation. Beside the internal stresses, can solidification modes, phase transformations, micro- and macro-segregation of elements during solidification and kinetics of precipitates caused by micro-alloying elements influence the weld quality [4-5]. The effect of alloying elements is another important topic in the evaluation of causes for crack formation during laser welding process. Impurities cause severe cracking in carbon and low-alloy steels even at relative low concentrations. The focus of this work has been to investigate the causes of crack- and defect-formation during laser welding of two structural steels, used in automotive applications. In the work has different laboratory characterization techniques been used and, combined with simulations by a specific software. The work has in addition to identification of defects and their causes, included identification of strategies for improvement of the laser weld quality [6-8].

2. Materials and Methods
2.1. Materials
Laser welded structural steels, mainly used for automotive components, were supplied by a Scandinavian company. The chemical composition of the two steels welded by laser is indicated in Table 1. The steels were laser welded against each other and, the resultant specimen was sectioned from the middle part, in the fusion zone (FZ). The specimen was analyzed longitudinally and perpendicularly to welding direction. This work was mainly focused on the identification of and causes for the defects formed during or after the laser welding process. Samples were prepared for metallographic analysis following the standard sample preparation process by grinding and polishing. The final polishing step was done by using colloidal silica suspension. In addition, the samples were etched with Nital 3%. In addition, a sample before welding was taken as a reference in order to compare the surface and the microstructure.

| Table 1. Chemical composition of the laser welded structural steels |
|------------------|---|---|---|---|---|---|---|---|---|
| %    | C  | Si | Mn | P  | S  | Nb | V  | Al | Ti |
| Steel 1 | 0.139 | 0.190 | 1.550 | 0.018 | 0.004 | 0.037 | 0.097 | 0.042 | 0.022 |
| Steel 2 | 0.29 | 0.25 | 0.75 | 0.035 | 0.035 | -  | -  | -  | -  |

2.2. Methods
2.2.1. Characterization techniques. Microstructure analysis of the specimens was carried out by using Nikon MA200 Optical Microscopy and Scanning Electron Microscopy (SEM JEOL IT 300). In the same way, SEM was used for applying the Energy Dispersive X-Ray Spectroscopy (EDX) for the qualitative and quantitative elemental analysis.
2.2.2. X-Ray Diffractometry (XRD). In XRD observations were monochromatic Cu-Kα radiation with 40 kV and 45 mA used. The anode diffractometer was used to scan the angular 2θ range of 20-120 degrees with scanning time of 20 minutes per each specimen. The resulting profiles were analysed by the High score plus software to obtain the exact position of the peaks. Peak positions and intensities of (111), (112), (200), (211), (220) and (130) planes were identified. Together with the Bragg’s law equation and the lattice parameters obtained, it was possible to calculate 2θ values of austenite, ferrite and martensite [10].

2.2.3. Microhardness test by Vickers. Measurements were performed in the welding direction across the FZ following the area close to the defects. Measurements in the cross section follows the FZ, the heat affected zone (HAZ) and the base metal (BM). The load applied was 100 g load (HV0.1).

2.2.4. Thermodynamic calculations. Prediction of phases under equilibrium conditions was calculated by using a commercial software (Thermo-calc). This program gives a general idea of the main phases formed during equilibrium conditions. Therefore, it was possible to calculate the presence of phases formed during solidification in local equilibrium condition with help of Scheil curves. In this simulation, some assumptions were made; no diffusion in the solid phase and fast diffusion in the liquid and it is assumed homogeneous. Calculation of the temperature-time-precipitation (TTP) curves was performed by TC-Prisma integrated in Thermo-calc. For this calculation, homogeneous diffusion of elements in the FZ was assumed. The purpose of this calculation was to present and compare, with the experimental analysis, the formation of the phases in order to find a way to relate the results with the behavior of the material during the laser welding process.

3. Results and discussions

3.1. Microstructural analysis

The microstructure of this material before welding consists of ferrite (F) and pearlite (P) in a banded structure, Fig. 1a. The microstructure after laser welding process consists of a mixture of tempered martensite (TM) and ferrite. Presence of untempered martensite (UM) was located mainly in FZ. Additionally, due to bainite (B) is difficult to distinguish from TM, there is a possibility to find some areas with B present in grain boundaries. Fig. 1b. The presence of UM is related to the rapid heating and cooling of the steel during the process. However, UM located in the FZ can be one of the reasons for crack formation during the laser welding process.

3.2. Identification of defects

Initially, defects found in the bulk, before laser welding process were located in the middle of the banded hot rolled structure, which correspond to manganese sulfide inclusions, normally present in this kind of steels. Fig. 2. The size of the defects was between 50-100 μm. Nevertheless, slags from the casting process can form some inclusions due to the short times at a high temperature or longer time at a moderated temperature during the process. In addition, cracks are located in the FZ on the steel after laser welding following trans- and inter- granular directions. Fig. 3. The length of the cracks are between 2.5 – 3.9 mm with 1 mm depth. Inclusions were found in the middle of the crack. Fig 3(b). These inclusions are identified as oxides because they are non-conductive. The analysis of the crack was performed in the cross section, perpendicularly to the welding direction. The FZ, HAZ and BM were identified, Fig. 4. It is possible to observe a difference shape of grains from the FZ to the BM. In all cases, the cracks follow the grain boundaries but some cracks are crossing the grains following random directions, inter- and trans-granular cracks respectively.
Cracks presented above were created during the process defined as solidification cracking mechanism. This kind of defects appear when the steel solidified caused by both shrinkage - and thermal-contraction. This kind of cracks normally form along the FZ grain boundaries but sometimes in the sub-grains. Also, is normally caused by the presence of stresses during the process; not to mention the effect of alloying elements and impurities on the weld which also affect the behavior of the steel during welding creating cracks. For this particular case, the location and direction of the cracks found is special and, those are not usually found in this kind of steels due to their low susceptibility to cracking in laser welding. However, the information and, the number of articles treating solidification cracking on structural steels during laser welding is limited [1-4]. Different causes can be detrimental for cracking formation in this kind of steels as the presence of brittle micro-constituent, in this case untempered martensite (UM) which was found in the FZ, and impurities formed during previous processing steps, which lead to segregation of MnS and inclusions. The kinetics of precipitation formation is very difficult to control because the fast heating and cooling during laser welding process. Thus, there is not enough time for precipitates to be formed by diffusion during the solidification and, there is not either time for existing precipitates to be dissolved during the heating cycle, and these can act as sites for crack formation. Finally, the control of process parameters is very important in order to have better control of the kinetics during solidification process such as heat input, laser power and welding speed [7-8].

3.3. Vickers microhardness tests
Vickers micro-hardness measurements using load of 100 g were performed. Measurements were applied to the samples before- and after- laser welding process in the longitudinal- and in the cross-sections with regard to the welding direction, respectively, Fig. 5 a. The distribution of the hardness values was uniform before welding, having an average of 214 HV (from 197 to 257 HV). The maximum values correspond to pearlite, while the lower values correspond to ferrite micro-constituents, Fig. 5c. For the welded samples, higher hardness values were found (from 218 to 352 HV). Presence of UM and TM might explain the highest hardness values. The FZ exhibit up to 352 HV, this value correspond to the presence of UM, while the HAZ exhibit up to 300 HV corresponding
to TM, Fig. 5b. Presence of UM is known for having an important influence on crack formation during laser welding.

3.4. Chemical and Phase analysis

Qualitative and quantitative chemical analysis by SEM-EDX was performed. In addition, XRD technique was applied to control possible phase changes during the laser welding process. EDX analysis exhibited the concentration of MnS, just for the specimen before welding with low presence of alumina, Fig. 6a. For the samples after laser welding, SiO$_2$ was found inside the cracks located in the FZ for both, longitudinal- and cross-section to the welding direction. These inclusions might affect the behavior of the material during solidification and act as sites for concentration of stresses and crack formation. The integrated peaks position, from XRD results, correspond to the planes (111), (112), (200), (211), (220), (130) for the three specimens before welding and FZ and cross section after welding as shown in Fig. 7a. The phases present in the material correspond mainly to retained austenite (111), (020) and (022) peaks and, to ferrite (110), (200), (211), (220) and (103) peaks, Fig. b- c. The identification of martensite with XRD technique is complex because the 2$\theta$ values are very close to those that correspond to ferrite. For the identification of martensite, in this case, some calculations were done by using the plane distance equation for tetragonal crystal cell, the lattice parameter and the Bragg’s equation. The presence of martensite could be related to (200) plane for the laser welded sample in the FZ, because this peak is showing wider, Fig. 7b. However, with this method, it was not possible to identify the presence of MnS but comparison with literature gave an idea of the possible location of these precipitates [10-11].

Figure 3 (a, b, c). SEM micrographs showing cracks in the FZ. Inclusions are located in the middle of the cracks (3c).

Figure 4 (a, b, c). Optical micrographs showing the FZ (a), the HAZ (b) and the BM (c). Cracks located in the FZ (4c).
Figure 5. Distribution of Hardness values in FZ, HAZ and BM (a-b) and before welding (c).

Figure 6. Chemical analysis by EDX on specimens before (a) and after laser welding process in the (b) longitudinal direction (FZ) and the (c) cross section.

Figure 7. XRD analysis data showing the (a) comparison of the specimens (b) before and (c) after laser welding process.
3.5. Thermodynamic calculations

Phases in equilibrium were calculated by setting the initial chemical composition and the proper thermodynamic database in thermo-calc software. Phases as austenite, ferrite, and cementite could be observed, Fig. 8. Further, precipitates of elements such as V, Nb, Mo, Ti and Mn can appear for this material. Those precipitates can be present in the material as carbides, nitrides or carbo-nitrides. MnS was another interesting phase. According of the experimental results, segregation of manganese sulfides were found in this steel (in hot rolling condition. Moreover, the segregation of this phase was observed to appear in the range of temperature from 1100 to 500°C, Fig. 9. In addition, precipitation kinetics was simulated by TC-Prisma by using assumptions as nucleation sites in grain boundaries, having FCC as matrix and interfacial energy of 0.5 J/m. Fig. 10 shows the formation of precipitates such as V and Nb (C, N) and MnS. The results give us a wide view of the formation of precipitates for this structural steel. Precipitation of V (C, N) is faster in comparison with Nb (C,N) and MnS precipitates, this forms in the range of 850-970 °C in approximately 10 seconds. However, a more detailed thermodynamic study of the precipitation and segregation formation for this material and its effect on crack formation after laser welding is recommended. Similarly, Scheil calculation was performed to simulate the evolution of phases during solidification process and to estimate the solute redistribution between the solid and the solidifying liquid phase. The solid fraction of delta phase appear at higher temperatures, that is related with the peritectic transformation because the amount of carbon in this steel. The solid fraction of austenite change from higher to lower temperatures while some other phases appear [13]. The segregation of MnS appears between 1350–1100 °C. Other elements as titanium carbo-sulfide (Ti₄C₂S₂) and V (C, N) was observed. Fig. 11 [12-13].

![Figure 8](image-url)
4. Conclusions
A complete study was carried out in order to identify the defects and their causes during laser welding of structural steels. The microstructural analysis of the steel before and after laser welding process was successfully performed. The hardness of the microstructures has been measured and related with the phases formed before and after laser welding. The Chemical- and phase- analysis by using SEM-EDX and XRD techniques was included. Thermodynamic calculations were done for predicting and comparing the phases formed in this steel in equilibrium and non-equilibrium conditions by Thermo-calc software. This in order to explain the performance of the steel during laser welding process.

Cracks were formed in the center of the fusion zone, longitudinally oriented, which is unusual orientation, following inter- and trans- granular directions. Those cracks were identified as solidification cracks. Causes of solidification cracks were related to the presence of untempered martensite formed in the fusion zone, which increases the risk for crack formation during solidification. The high concentration of Mn and S found in this steel before welding increases also the susceptibility for crack formation. Precipitates containing Si and O have been found on the crack surfaces and, their origin has not been possible to explain in this work.

The presence of these elements together with the brittle micro-constituent and the fast solidification during laser welding process, create tensile stresses by volume shrinkage in the fusion zone, causing the formation of the cracks identified.

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