Measurement of Residual Stresses in Linear Friction Welded 18CrNiMo7-6 Steel Chains

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Abstract

Residual stresses (RS) are the stresses that remain in a component after removing all the external solicitations. The presence of this stress field in a part is often the main reason for compromising its in-service performance, reliability and life extent. They can also influence negatively the fatigue strength of a component, stress corrosion cracking and the crack propagation velocity itself. Therefore, knowing its magnitude and nature in detail, is an important matter to assure the pretended attributes during the whole life of a component.

There were analysed 4 different manufacturing stages of Linear Friction Welded chain links: "As Forged", "As welded with flash", "As welded without flash" and after PWHT. The methods used to characterize the residual stress field were the Hole-Drilling

The results from the hole drilling technique clearly showed that independently from the side of the chain link (left or right) the residual stress field was the same. Also between the top and bottom regions of the chain link, symmetry was observed regardless the non-circular geometry of the chains studied. Close to the weld centre line, the compressive stresses present in the "as forged" condition switched to tensile due to the welding process. Away from it, there were not observed any changes between "as forged" and "as welded without flash". No changes were observed in the flash removal process. The PWHT uniformizes the residual stress field along the whole weld region. The x-ray diffraction results did not show relevant changes between each of the conditions studied.

Keywords

Residual stresses; Hero chain links; Manufacturing Stages; Hole-drilling; X-ray diffraction; Linear Friction Welding

Highlights

- Linear Friction Welding of 18CrNiMo7-6 was performed.
- It was studied the influence of the welding process, flash removal and post weld heat treatment in the stress field;
- Hole-drilling method was used to characterize the stress field until 1mm depth of the chain link;
- X-ray diffraction measurements were performed to study the stress state at the surface of the specimens;

1. Introduction

Joining steel components has been one of the most important manufacturing processes in industry since the steel demand worldwide keeps increasing until the present day. Although the usage and development of lighter, equally resistant, and not so harmless to the environment materials is also increasing, there are many applications where the use of steel is inevitable. Therefore, joining and forming steel are and will be, at least in a recent future, one of the biggest sources of investigation and research. The first welds of metallic material date back to the Bronze Age. Since the beginning of the 19th century a lot of favourable discoveries to this topic have been made. Nowadays, optimizing the performance of a component by enhancing its relevant characteristics and reducing its costs is a top priority to most engineering industries. Therefore, discovering new joining processes and improving the existent ones is until this day a great topic of discussion [1].

Due to all the facts mentioned before, solid-state welding processes have seen an increasing development in its scope of applications since it has numerous advantages when compared to other commonly used joining processes. It does not require fluxes, protection gases or filler materials which which traduces in a substantial reduction of costs. When reporting to Linear Friction Welding (LFW), the industrial applications of the process were limited for a long time to joining turbine blades to its disks (blisks)[2], [3]. Most recently, in 2007, there was also relevant investigation in the application of LFW to near-net-shapes. Since it can reduce material costs up to 90% when compared to traditional machining procedures [4]. Nowadays, the industry is focusing in the improvement of the productivity without compromising the performance of the component. Therefore, LFW scope of applications is increasing, since it provides superior quality welds (when compared to the resistance welding processes commonly used in chains) in a much more reduced timespan. Since solid-state welding processes bring many advantages when compared to conventional ones, multiple industries are studying the possibility to use LFW in their production chain. These facts make the knowledge about the residual stress field in this type of welded structures an important subject of investigation. The welding parameters for the investigated case were already optimized. Thus, it is not necessary to inspect this topic. If it is pretended to research different LFW applications these parameters should be evaluated and optimized [1], [5].

This work intends to study the residual stress field in the main different stages of steel chains manufacturing: as forged initial condition, as welded condition without removing the flash, as welded condition after the flash is removed through a standard procedure and after the post welding heat treatment (PWHT) is applied. The methodologies used to measure the residual stresses were: the hole-drilling (HD) technique, which is an evasive method and allows measuring the stress state in a region close to the surface of the component, and the x-ray diffraction (XRD) method that measures that stress field without damaging the specimens used. These methods were chosen considering its suitability for the case and the equipment available at the institution where the investigation was performed. It was also taken into consideration that the data provided by HD at the surface of the specimens, is more susceptible to measurement errors. In such wise, both tests complement each other. Since there is no literature available related to residual stress measurements in this LFW steel alloy 18CrNiMo7-6, the work serves the intent to positively contribute to the lack of knowledge on this subject, as well as to expand the applications of the LFW process.

The use of LFW allows the joining of chain links with different geometries that can provide a better wear resistance and increased lifespan [6]. The type of chain links studied in this dissertation was the pewag Hero Chain shown in Fig. 1 below. It is also shown the increased wear resistance due to the application of this joining process. The different phases of the process are shown in Fig. 2.

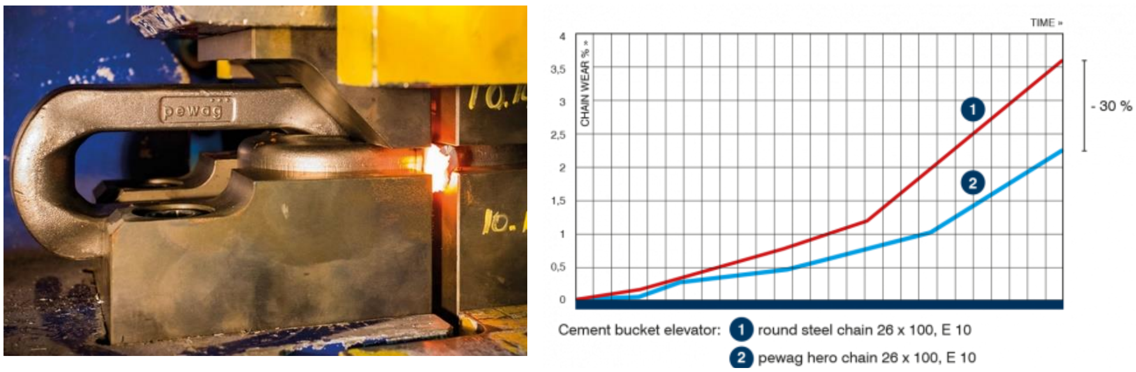

Figure 1-Illustration of the LFW process applied to hero chains and its increased wear resistance

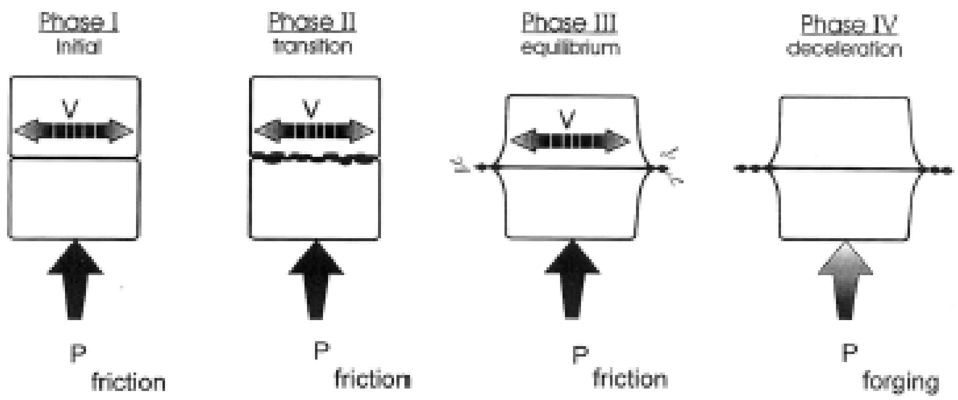

Figure 2-Illustration of the different phases of the LFW process

Regarding the scope of this dissertation, the most suitable mechanical method to measure residual stresses is the hole drilling method. The method is characterized for being the cheapest and most practical to implement, thus providing reliable and useful information about the residual stresses near the surface of the chain. It can be classified as a semi destructive test (SDT) [7] since it causes minimal damage to the sample. Considering the application of the chains studied, it is known that crack initiation sites are regions where the highest stress concentration factors are obtained. Previous investigations concluded that the junction of the linear friction welded component with the flash, was prone to be one of those crack initiation sites. Hence, the residual stresses at the surface of the chains are critical to the stress concentration factor in these regions. Standing in the non-destructive test category, x-ray diffraction is a test that provides information about the crystallographic structure, chemical composition and physical properties of materials. Bragg's formulation of X-ray diffraction was proposed by William Bragg in 1913 [8]. This formulation relates the scattering of an emissive source of x-ray (which has comparable wavelength to the interatomic distance in a crystalline material) with the scattering angle Θ and the spacing between the crystallographic planes d. If residual stresses exist on the sample, then the d spacing will be different from the one in an unstressed sample.

2. Experimental details

18CrNiMo7-6 half chain Hero links with the dimensions presented in the following Fig. 3 were used in this work. The nominal chemical composition of the material is presented in Table 1.

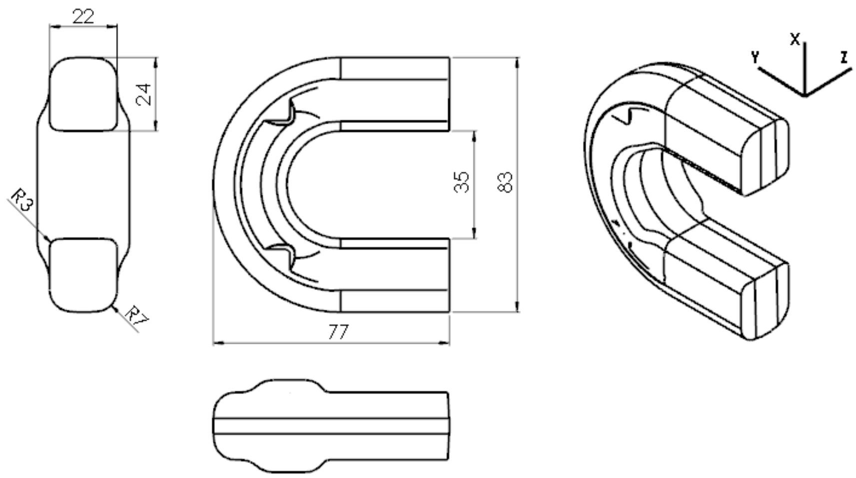

Figure 3-Geometry of the half chain links studied

Table - 1 Nominal chemical compositions of base material (wt.%).

Alloy	C	Mn	Si	Ni	Cu	S	Mg	Cr	Mo	P
18CrNiMo7-6	0.18	0.58	0.27	1.62	0.17	0.008	2.2	1.76	0.250	0.011

The joints were performed at pewag in a LFW prototype machine. Each half chain link was subdivided in 6 different areas where it might be relevant to analyse the behaviour of the stresses. Looking from the stationary part as the origin into the moving one, the locations are defined as it follows:

- Top Left (**TL**)
- Top Right (**TR**)
- Bottom Left (**BL**)
- Bottom Right (**BR**)
- Left Side (**LS**)
- Right Side (**RSi**)

The following Fig.4 explains the location of those areas:

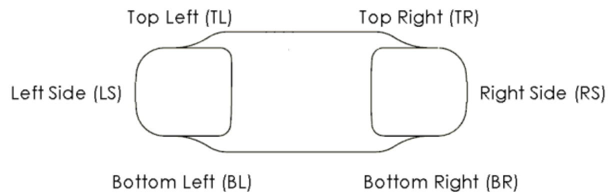

Figure 4-Locations where the hole drilling measurements were performed

The HD equipment used was a SINT MTS 3000 and the measurements were performed according to the ASTM e837 standard. The constitution of the equipment is listed below [9]:

- An optical-mechanical drill to physically form the hole
    - This system contains a stepping motor and is powered by an air turbine that allows drilling at 350000 rpm;
- An electronic controller;
- Controlling and operating software for the hole drilling;
- Reprocessing software that allows the calculation of residual stresses through the strain relieved;
    - The system allows the calculation of these stresses using four different algorithms;

All the measurements are described by its location followed by the distance to the weld center line (WCL) and the prefix **S** or **M** concerning the stationary and moving parts (respectively). The strain gage rosettes used for the measurement were HBM RY3 and RY2 circular and rectangular respectively:

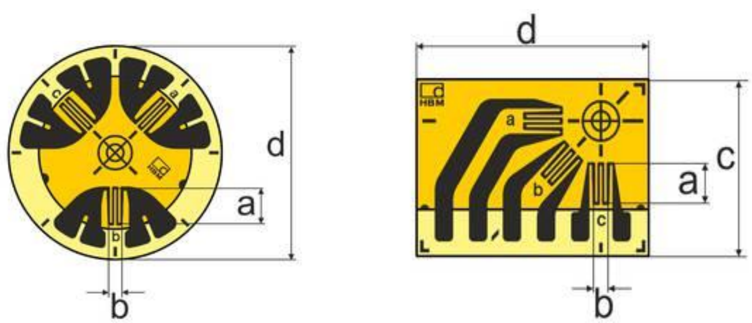

Figure 5-Strain gage rosettes used in the HD method

The XRD was performed according to the EN 15305:2009 [10] standard premises. The equipment used was a Stresstech G2 which is suitable for laboratory, factory or field use since it is a portable equipment and can easily be assembled by one person alone. It has the advantage of having the possibility to perform measurements in confined spaces and in complex geometries. The measurements were performed at MCL (Material Center Leoben Forschungs GmbH).

3. Results and Discussions

In this section the main results obtained for both residual stress measurement techniques are presented. A brief discussion of the results is also performed where the changes observed in each of the conditions studied are explained.

3.1. As forged initial condition (F):

The results evaluated are similar in every location, showing that the maximum absolute values of each one occurs near the surface of the specimen in the x direction. The difference in absolute value for every location is less than 100 MPa. This value is negligible due to measurement errors so it is valid to assume that the residual stresses present on each location of the samples are the same. These curves, presented in Fig. 6 show a typical behaviour of a shot peened surface [11], [12] where the maximum value of the compressive stresses is strongly dependant on the shot peening conditions used. Therefore, there were not performed further measurements in the previously planned locations. In shot-peened samples the highest stress values remain near the surface of the component which is in good agreement with the results.

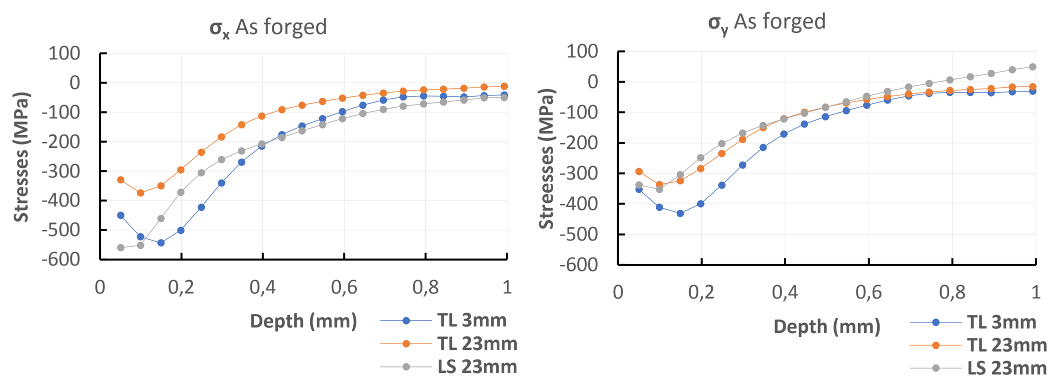

Figure 6-Residual stress results a) σx and b)σy for three different locations (as forged condition).

3.2. As welded condition with flash (A):

It is pretended to evaluate the influence of the welding process in the residual stress field. Therefore, there were carried measurements following the same procedure as before in the as welded samples. The following Fig. 7 shows the comparison of the residual stress profile 3mm away from the WCL in the **F** and **A** conditions. These measurements showed a clear tendency of relaxation of the compressive residual stresses caused by the shot peening. When comparing the stress field near the surface of both conditions, $\boldsymbol{\sigma_x}$ decreases from a maximum absolute value of around -400MPa to -100MPa. This decrease in absolute values can be explained by the heating of the component during the friction phase of the welding process as well as by the axial shortening when joining both half chain links [13]. It is proven that this reduction in the compressive stresses is caused by the welding process by comparison of the residual stress field in regions far away from the heat affected zone (HAZ) for both conditions. In these regions, both $\boldsymbol{\sigma_x}$ and

σ_y suffer only a slight variation that can be considered negligible (around 100 MPa). These results are shown in the Fig. 8 below.

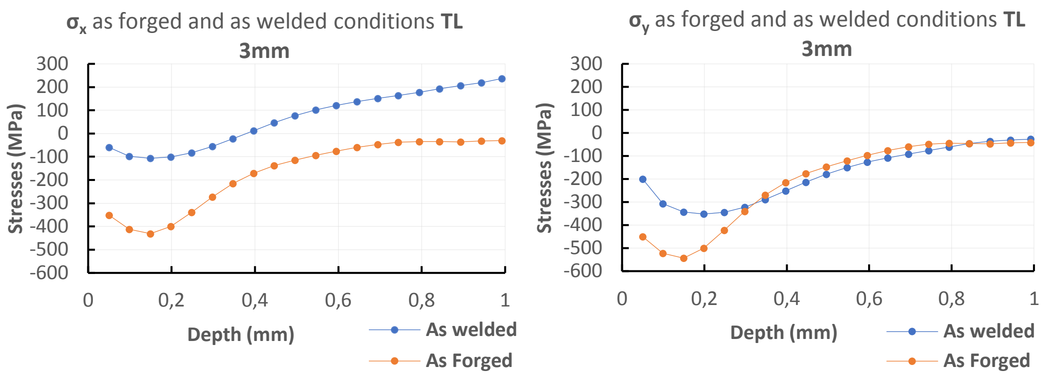

Figure 7-Comparison between a)σx and b)σy for both the as forged and as welded conditions 3mm from the WCL

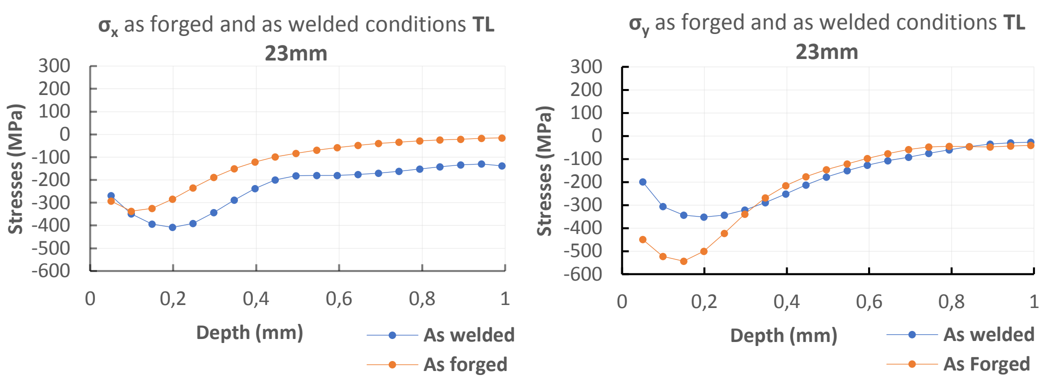

Figure 8-Comparison between a)σx and b)σy for both the as forged and as welded conditions 23mm from the WCL

Far away from the weld centre line, both the transverse and parallel residual stresses show a variation of less than 100 MPa. As it was expected, the HAZ in the LFW process is reduced when compared to non-friction welding processes. This expectation was experimentally confirmed since away from the WCL (also away from the HAZ), the residual stresses are nearly the same even after the welding process.

In the as welded with flash condition, there were performed measurements at the exact same distance of the weld centre line (3mm) in both the stationary and moving parts of the chain link. The results shown in the Fig. 9 below show that the process induces the same residual stresses in both **M** and **S** which means the process can be considered symmetric. There was a slight variation of less than 100 MPa in both sides that can be neglected as explained before. It was also proven symmetry in the RS field between the **TL**, **BL** and **TR** as shown in Fig.10.

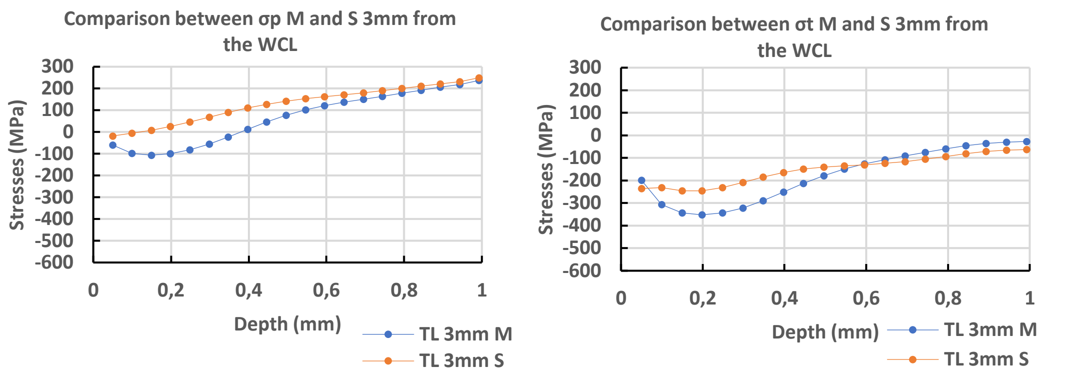

Figure 9-Comparison between a)σx and b)σy in both the stationary and moving side 3 mm away from the WCL

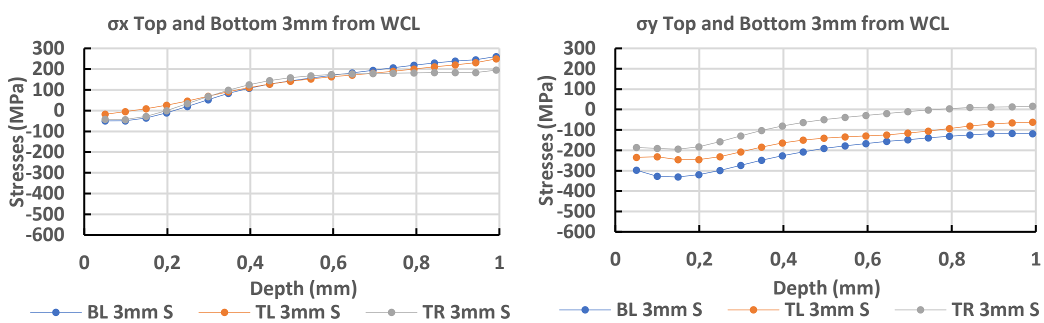

*Figure 10-Comparison between a)σx and b)σy in **TL,TR, BL,** 3mm from the WCL.*

3.3. As welded condition without flash (N):

In this chapter the influence of the flash removal in the residual stress field is evaluated. A direct comparison of the stress results between the **A** and **N** conditions was performed. It is expected that the differences in the stress results may occur closer to the WCL. Thus, only the measurements as near as possible to the WCL are shown (3 mm away from it). Analysing the graphs from Figure 11 there seems to be no influence of the flash removing process in the RS field. The differences observed are the typical differences to obtain in the HD method (100 MPa) that can be neglectable.

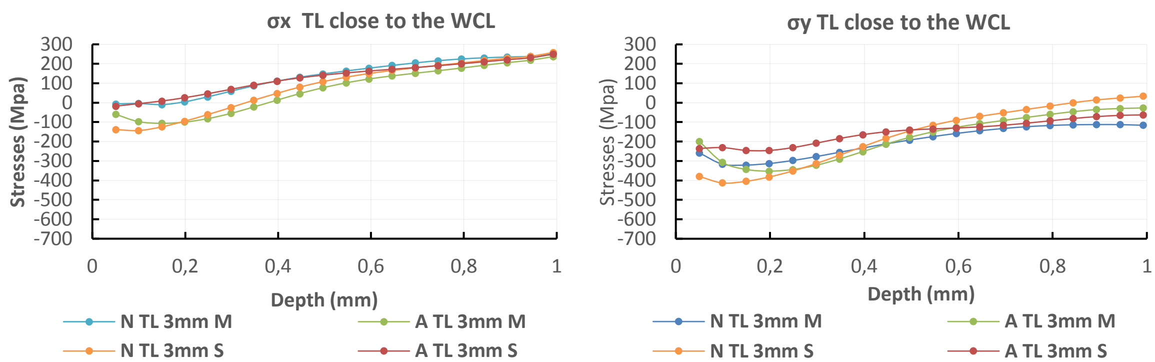

*Figure 11-Comparison between a)σx and b)σy in **A** and **N** conditions.*

3.4. As welded condition without flash after PWHT (P):

The HD results obtained for the **P** condition (see Figure 12) show a uniformization of the stress field not only along the whole weld region but also when comparing the x and y directions. The PWHT performed switches the tensile stresses present close to the WCL due to the LFW process into compressive (-600 MPa difference). When comparing the values of this condition far away from the WCL there is still a slightly higher maximum absolute value in this condition.

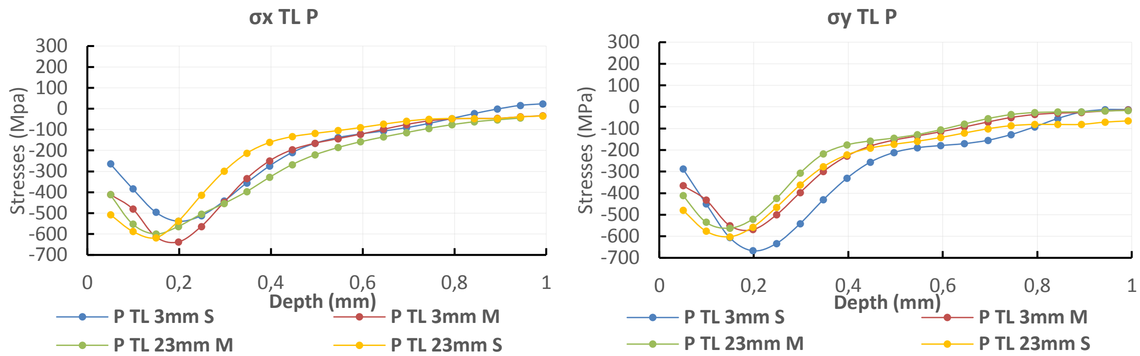

*Figure 12- Comparison between a)σx and b)σy in **P** condition.*

3.5. X-ray diffraction results:

The xrd measurements presented in Figure 13, do show some differences between the different conditions. Although there is no pattern besides the lower maximum amplitude of the **P** condition. Considering that the penetration depth of the x-ray is around 5μm, there seems to be no influence of the welding process, nor the flash removal nor the performed PWHT at the surface of the chain link. The differences observed between the conditions can be explained by differences that were not controllable since the forging procedure was performed.

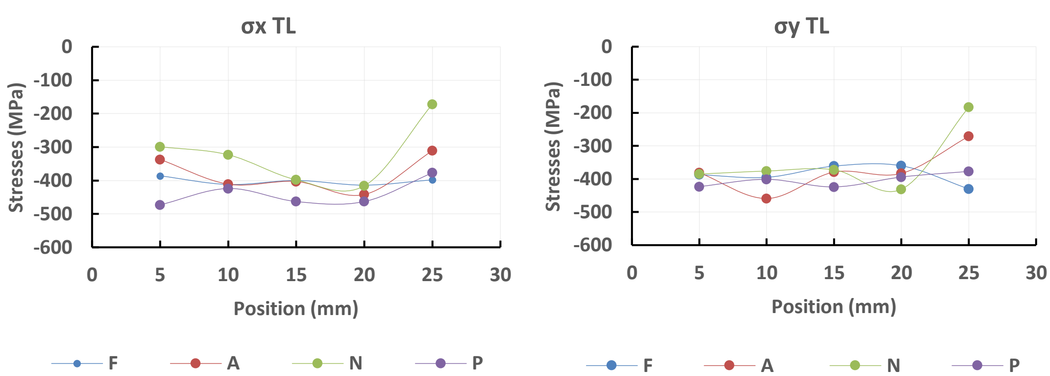

Figure 13 - XRD results for all the conditions studied

4. Conclusions

The effects of the LFW process, the standard procedure used by the company to remove the flash, and the PWHT performed in the residual stress field were evaluated. The conclusions of this evaluation are listed as follows:

- The HD method showed that the **F** condition had similar residual compressive stresses in all the locations measured. It confirmed the shot peened condition of the samples;

- It was proven that due to the welding process the residual stresses switched from compressive to tensile near the WCL. Away from it, the stresses did not change significantly. This proved that the joining process has a great degree of influence in the RS field
- There was observed a similar profile of the RS field in both the stationary and the moving half chains although a significant difference (slightly bigger than 100 MPa) was observed in the first 0,4mm depth that might be justified by the wear in the clamping system.
- Symmetry was obtained when comparing the RS field of the Top and Bottom sides of the chain link. In the x direction there was only observed a difference of less than 50 MPa in the first 0,2mm of depth in the hole drilling and around 10 MPa at the last 0,2mm. In the direction of the forging force there is a constant difference of less than 100 MPa along the whole depth of the hole which can also be neglected;
- When comparing the left and the right regions of the chain links, symmetry was also observed. In the x direction, there was a slight difference in the first and last 0,2mm of the hole depth. In the y direction, an almost constant difference of less than 100 MPa was obtained along the whole depth of the hole;
- The flash removal procedure used by the company seems to have no influence on the RS field closefrom the WCL. It also seemed to not cause any differences whether considering the x or the y direction;
- Away from the WCL, in the **P** condition, the RS field has higher values of compressive stresses when compared to conditions not subjected to PWHT.
- The PWHT applied switches the tensile stresses due to the welding process into compressive stresses.
- The PWHT applied uniformizes the stress field in every location (either on the WCL or away from it). It also uniformizes the hardness along the whole weld. Both the hardness and the RS field seem to have no significant differences between the different locations measured (close and far away from the WCL) after the PWHT was applied.
- The PWTH seemed to have influence only in the stresses measured close to the surface (0,05 to 1mm) of the component. Inside the chain link all the results tend to the same values.

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