Experimental research on reconditioning transmission axles by MAG robotic welding

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Abstract. The current paper presents the experimental program conducted in order to determine the welding technology for shaft bond wheels, of Cr and Ni low alloyed steel, in enhanced condition. The material that makes up the shaft bond wheel is in laminated state, with a diameter of 70 mm and a high tendency to cracks when subjected to welding. During exploitation, these axles are subjected to stress and fatigue which imposes developing materials with equal resistance as well as avoiding concentrators in the joint design. The steel transmission shafts, butt welded together, contain Fe-1.7\%Cr-2\%Ni type with a 0.4\%C, respectively Fe-0.7\%Mn-1\%Cr type with 0.3\%C, with hardness approx. 250HB on the shaft and 350HB on the axle. The preheating and inter-pass temperature, combined with mechanical characteristics of welded joints, that have similar resistance, was performed according to SR EN 1011-2-2004, using the help of equivalent carbon computational relations. Fractometric analysis of deficiency areas extracted from parts used in exploitation, at the beneficiary exploitation site, due to defects, highlighted "fish eye" defects, fatigue cracks, that determined choosing this welding technology, namely robotic, in protective gas environment, Corgon 18 – 82\%Ar and 18\%CO\textsubscript{2}, using EN ISO 16834-A G694MMn3Ni1CrMo wire with a diameter of Φ1.6 mm. Welding was performed by maintaining 150°C temperature between layers, at a welding speed of 280 mm/min, power 200±10A, wire feed speed 3.7 m/min, in protective gas, Corgon 18 with a 18.22 l/min flow. The joint was designed so it will have minimum concentration areas and assure cooling of welded zones, after the joint was completely filled. After the repair we extracted samples from the joint, in order to test the weld quality and assimilate the technology. Metallographic and compositional analysis performed on specific areas highlighted improved structures in the center of the weld – zone 2, which ensures a proper tenacity of the joint and a hard coat, at the exterior, that favors the good operation of the assembly under critical fatigue conditions. Results obtained confirm and recommend implementing the developed welding technology into industrial environment.

1. Introduction

Transmission shafts used in transport vehicles are subjected, in exploitation, to mechanical fatigue and are made from low alloyed steels in enhanced condition. The steel transmission shafts, butt welded together, contain Fe-1.7\%Cr-2\%Ni type with a 0.4\%C, respectively Fe-0.7\%Mn-1\%Cr type with 0.3\%C; [1] the welding technology previously applied lead to the appearance of defects type "fish eye", determined by the high content of diffusible hydrogen, according to tests done on damaged shafts taken out of exploitation, [2]; as well as softening the heat affected zone (HAZ) by exceeding the temperature during welding [3]; both defects constituted the main cause that led to cracks that further transformed into the breaking by fatigue of the reconditioned shaft [4].
Low alloyed steels with Cr or Ni and Cr present a high tendency to cracks by welding [5], fact that imposes special measures to reduce brittle factors, [6], namely the content of diffusible hydrogen, the degree of three axial tensions from exploitation, [7] respectively reducing the cracking tendency of the constituent elements [8].

The diffusible hydrogen from welded joints results from the filler material, respectively from the surrounding environment [9] Reducing diffusible hydrogen content can be performed by using filler materials with low hydrogen content, namely wires for welding with protective gas - Corgon 18 – 82%Ar and 18%CO₂ [8,10] Specific joint zones are subjected to complex stress that result from overlapping remaining tensions from the welding process with those from exploitation [2,7].

Reducing the three axial stresses can be achieved by properly choosing the welding technology, namely the chamfer geometry, the preheating and inter-pass temperature, as well as the heat input [11].

The nature and morphology [12] of structural constituents is mostly determined by the cooling rate of welding layers that, according to SR EN 1011-2:2004 can be appreciated by cooling time, tsₕ that must be checked for each case by qualifying the welding technology, according to EN 288-8:1997. Controlling the welding technology is mandatory, in this case using robotic welding [13] and coordinating the execution with results obtained by monitoring technological parameters, in the stage of developing the welding procedure and programming the robot arm, according to specifications from manufacturing conditions in industrial environment.

It is known [14] that the superficial hardening of mechanical wear subjected zones determines a significant raise in wear resistance of processed shaft, [15] phenomena obtained in this case, by carefully choosing the welding parameters of the last layer.

2. Experimental program
The experimental program was structured in three stages: first analyzing the deteriorated transmission axles, of the cracks, hardness, chemical composition tests, as well as well as assessing the weld, performed inappropriately, on a previous repair; second is to determine the welding technology and its quality; the third, to develop welding technology for layer deposition through an experimental program and applied welding technology.

2.1. Analyzing the transmission shafts
The first stage analyzed tram shafts made from Cr and Ni low alloyed steel, in enhanced condition, during exploitation these are subjected to stress and fatigue which imposes developing structures with similar resistance and avoiding concentrators in the joints design. The damaged observed on the transmission shafts highlighted a fragile crack in the base material and also observed signs of fatigue on the outer ring, with the appearance of "Fish eye" defects - white spots (diffuse hydrogen - resulting from inappropriate welding). It can be concluded that the break was caused by shock.

![Figure 1. Chemical composition.](image)
2.2. Determining the repair technology

In order to choose the appropriate welding technology a chemical analysis of the materials needed to be performed, results are presented below, in Figure 1.

After we determined the chemical composition of the transmission shafts (AISI 4300 and 4140) and consulted the materials data sheet, the welding technology was chosen (Figure 2), in this case robotic MAG welding with protective gas (Corgon 18), maintaining the temperature between passes under 150°C and using wire type: EN ISO 16834-AG 694Mn3Ni1CrMo.

![Figure 2. Welding material and process.](image)

After carefully choosing the welding technology and filler material, it is necessary to establish the chamfer geometry (Figure 3) of the two, shaft and axle, which are to be welded, if pores appear these must be removed mechanically.

![Figure 3. Chamfer geometry.](image)

| Current [A] | Wire feed speed [m/min] | Welding speed [mm/min] | Wire tip [mm] |
|------------|-------------------------|------------------------|---------------|
| 200        | 3.7                     | 280                    | 18            |

The welding joint geometry was chosen in order to obtain a fully welded section, almost equal to the surface of the axle section. Other considerations for choosing this joint configuration were the reduction of the number of welding layers required and the accessibility of the welding torch in the central axis of the welding materials. The tram shafts were robotic MAG welded using the parameters presented in Table 1 and supplies described in Table 2.
Table 2. Materials.

| Filler material          | Mn$_3$NiCrMo AWS ER 100 |
|--------------------------|--------------------------|
| Diameter                 | 1.6 mm                   |
| Protection gas           | Corgon 18 (82%Ar and 18%CO$_2$), 22 L/min |
| BM AXLE                  | AISI 4300                |
| BM Shaft                 | AISI 4140                |

The transmission shafts that needed to be welded, required a total of 42 layers, presented as follows: welded joint scheme – layer deposition scheme - presented in the Figure 4, welded layer 5 – cleaned / final weld – rough, Figure 5.

After performing the welding operation, it is recommended to cool the joint in a controlled manner, to avoid hardening the final layer, if this is not required.

The joint was processed for macroscopic analysis, Figure 6, and then performed hardness tests on the base materials and weld, in order to determine the quality of the achieved joint.
Macroscopic section analysis highlighted pores in the base materials, lack of penetration between layers and in the middle of the chamfer geometry, presented above, in Figure 7.

Microscopic analysis was performed using the optical microscope HIROX, enhancement 100x and 500x, Vickers hardness test, analysis method: structure study, metallographic samples: AISI 4043; AISI 4130/4140; Mn3Ni1CrMo.

Table 3. Microscopic optical aspect in cross-section.

| Enhancement | 100X | 500X |
|-------------|------|------|
| 1 | BM- Shaft | BM- Shaft |
| 2 | Shaft HAZ | Shaft HAZ |
| 3 | Weld | Weld |
Table 3. Microscopic optical aspect in cross-section.

| Enhancement | 100X | 500X |
|-------------|------|------|
| 4           |      |      |
| Chamfer area|      |      |
| Weld – lack of penetration |      |      |
| 5           |      |      |
| Axle HAZ    |      |      |
| Axle HAZ    |      |      |
| 6           |      |      |
| Axle        |      |      |
| Axle        |      |      |

Table 4. HV 10 micro-hardness values.

| Area                      | 1   | 2   | 3   |
|---------------------------|-----|-----|-----|
| BM Shaft                  | 262 | 254 | 254 |
| BM Axle                   | 339 | 333 | 333 |
| Interior weld             | 287 | 287 | 283 |
| Center weld               | 274 | 274 | 274 |
| Exterior weld             | 262 | 258 | 258 |
| HAZ Shaft zone 1          | 317 | 312 | 317 |
| HAZ Shaft zone 2          | 333 | 351 | 342 |
| HAZ Shaft zone 3          | 339 | 339 | 345 |
| HAZ Axle zone 1           | 351 | 351 | 351 |
| HAZ Axle zone 2           | 322 | 330 | 333 |
| HAZ Axle zone 3           | 503 | 473 | 450 |

The microscopic optical analysis highlights a perlitic-feritic structure of the developed joint. The metallographic analysis highlighted recurrence structures determined by thermal treatments of the interior layers towards the exterior ones. We also observed micro cracks, lack of melting and small
pores that do not influence significantly the quality and/or functionality of the axles in exploitation, due to the good tenacity of the welded joints specific areas. At the same time we noticed defects of sample processing that can be mistaken as cracks that also do not influence the welded joint in exploitation.

Analyzing the above presented data highlights normal values for the investigated zones, as well as a variation, without jumps, of hardness values in the middle area of the joint, thus assures a significant reduction of the risk of concentration factors occurrence. The exception is the final layer, that has a relatively high hardness value, compared to the rest, unaltered by thermal treatments between layers, nor post-weld, for reasons of assuring a rough final layer, it substantially raises the resistance to wear of the axle, in exploitation.

Table 5. Measured values tensile tests.

| No. | Area       | Test | Mark | Value [N] |
|-----|------------|------|------|-----------|
| 1   | BM Axle    | Tensile | T7   | 21950     |
| 2   | BM Axle    | Tensile | T8   | 21400     |
| 3   | BM Axle    | Tensile | T9   | 21400     |
| 4   | BM Axle    | Tensile | T4   | 14850     |
| 5   | BM Shaft   | Tensile | T5   | 14860     |
| 6   | BM Shaft   | Tensile | T6   | 14700     |
| 7   | HAZ Axle   | Tensile | T3   | 14450     |
| 8   | HAZ Shaft  | Tensile | T2   | 14620     |
| 9   | Weld       | Tensile | T1   | 14750     |

Figure 8. Impact bending values and section scheme.

As a result of measurements of impact-bending test at -20°C (Figure 8) on the base materials and welding, depending on the heat-affected areas, it can be noticed that the axle - main base material of the transmission shaft, presents the smallest values measured at impact bending, i.e., it has a fragile shock behavior.

The base material of the shaft used to repair the axle, due to the different type of material, exhibits a more ductile behavior than the axle, which means increased shock resistance. It is also possible to observe the same ductile behavior in the heat-affected areas (HAZ), for both base materials and welding.
Table 6. Charpy impact strength test values.

| No. | Area   | Test           | Mark | Value | Measuring unit |
|-----|--------|----------------|------|-------|----------------|
| 1   | BM     | Impact strength| BM21 | 22    | [J]            |
| 2   | Axle   | Impact strength| BM 22| 22    | [J]            |
| 3   |        | Impact strength| BM 23| 20    | [J]            |
| 4   | BM     | Impact strength| BM 11| 122   | [J]            |
| 5   | Shaft  | Impact strength| BM 12| 90    | [J]            |
| 6   |        | Impact strength| BM 13| 72    | [J]            |
| 7   | HAZ    | Impact strength| M7   | 76    | [J]            |
| 8   | Axle   | Impact strength| M8   | 100   | [J]            |
| 9   |        | Impact strength| M9   | 114   | [J]            |
| 10  | HAZ    | Impact strength| M4   | 126   | [J]            |
| 11  | Shaft  | Impact strength| M5   | 90    | [J]            |
| 12  |        | Impact strength| M6   | 164   | [J]            |
| 13  |        | Impact strength| M1   | 90    | [J]            |
| 14  | Weld   | Impact strength| M2   | 88    | [J]            |
| 15  |        | Impact strength| M3   | 90    | [J]            |

Figure 9. Hardness values HV 10.

Figure 10. Tensile values.

The values of the measured HV 10 micro-hardness (Figure 10) are very close to all measured areas of interest, with a small exception for the HAZ axle exterior area – zone 3, where the last surface weld was made and the maximum value of 150°C, between the welding layers, was exceeded. The cooling
of the welded assembly has not been controlled, which favored the hardening of the last layer. By exceeding the maximum temperature between passes, the materials are thermally influenced, and there is a risk of hardening the area, which leads to the embrittlement of the material.

Also, micro-hardness values close to those of the base materials can be observed in the heat-affected and welded areas, which means a correctly chosen welding regime and stability and process consistency as long as the process parameters are maintained constant for each pass.

Tensile tests (Figure 10) revealed a superior strength of the axle compared to the shaft and weld. In the case of the welding, thermally affected zones and shaft, identical values can be observed, which confirm that the welding technology chosen, for the two different types of materials, was adequate.

Conclusions
The values measured by experimental test performed, are consistent and correlated; a hard material (in this case the axle) tends to have a more fragile behavior towards shocks but higher values in the case of tensile or compression loads. It can be concluded, from tests performed, that we obtained 70-80% efficacy, in the case of repairs with this type of shaft material, different from the base material of the axle.

Research performed resulted in the future qualification of the robotic welding technology in protective gas environment of transmission shafts made from low alloyed steels with Cr and Cr with Ni, in enhanced state, from the composition of transport vehicles – trams. Experiments performed in order to future qualify the technology, confirmed resulted technological prescriptions in the process of developing the welding technology.

Welding with an inadequate material and/or technology determined the appearance of an exceeding amount diffusible hydrogen, over the safety limit, thus the appearance of defects type "fish eye" that lead to cracks and in the end, damaging the transmission shaft.

The technology used to repair the damaged shafts determined the development of a joint with a favorable transition of hardness in specific areas and a minimum effect regarding tension concentrators.

The high number of welding layers from the consistency of the joint favored the annealing of deposited layers, as well as enhancing the plasticizing performance of the welded joint. The welding technology applied in order to deposit the last layer favored the development of a hard crust, which is beneficiary, in this case due to the nature of exploitation of the transmission shafts, namely increasing the shafts resistance to wear.

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