Repair attempts of cold crack on forklift made of C45 steel: Case study

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1. Introduction

Cold crack is a common issue in welded structures. A cold crack is a spontaneous crack that occurs at temperatures that are below 200°C after solidification is complete after welding. Problem with cold cracking is that it develops hours or days after the weld has been made. This cracking is also known as "delayed cracking." Cold cracking is occurring in all ferritic and martensitic steels, such as carbon steel, low alloy steel and high alloy steel, unless adequate precautions, mainly preheating, are performed [1]. Cold cracks are most often caused by residual stress.

Base material C45 steel by itself has a tendency towards cold cracking, due to high carbon content. For this reason it is crucial to perform adequate preheating treatment.

This was the case here, i.e. the crack was caused by residual stress during production, and this could be prevented by base material preheating for the purpose of reducing the cooling speed of the weld. This is common practice for prevention of cold cracking, and very important step in production, since all cracks need to be repaired, and that introduces additional production costs and is a time-consuming process [2-6]. Because it was previously mentioned that cold cracks are caused by residual stress, the fork of a forklift needed to be observed for some time after repair welding, as it will be explained later in more details.

Weld dimensions, recommended welding processes and choosing of filler material and other welding parameters were adjusted to the base material and the exploitation conditions under which the fork was working.

In this case, non-destructive testing (NDT) is performed after reparation, after one and also after three months in exploitation. Non-destructive testing is a descriptive term used for the examination of materials and components in such a way that allows materials to be examined without changing or destroying their usefulness. NDT testing can be used to determine the size and/or location of surface and subsurface flaws and defects [7, 8].

2. Base and filler material properties

2.1. Base material

Base material C45 is an unalloyed medium carbon steel, which is also a general carbon engineering steel. C45 is a medium strength steel with good machinability, usually used for medium loaded parts of higher dimensions [9]. Chemical and mechanical properties of this base material are shown in tables 1 and 2 [10].

Table 1. Chemical composition of C45 [%].

C	Si	Mn	P_{max}	S_{max}.
0.42-0.50	0.15-0.40	0.5-0.80	0.04	0.04

Table 2. Mechanical properties of C45.

Yield stress $R_{p0.2\%}$ [MPa]	Tensile strength R_m [MPa]	Elongation [%]	Toughness [J]
325	500-700	20	21

2.1.1. *Carbon equivalent C_{eq}*

Steel weldability is estimated by the Carbon equivalent (C_{eq}) and represents the tendency toward the forming of brittle phases during welding [11, 12]. This is especially important in the case of steels such as this one, due to its high carbon content. Carbon has the highest influence on the behaviour of steels, hence the effect of remaining alloying elements is reduced to its equivalent, i.e. the C_{eq}.

If the calculated value of C_{eq} is less than 0.3, it can be assumed that all requirements are fulfilled for obtaining high quality welded joints without the need of applying special technological measures (i.e., the steel has good weldability). If C_{eq} ranges between 0.3 and 0.5, preheating or other measures are necessary, in order to achieve the required quality levels. In the case of C_{eq} greater than 0.5, welded joints of required quality are not impossible to make, but special technological measures are required.

For steel C45, the calculated carbon equivalent according to the Seferian method [13], was 0.47. This value corresponds to the second group ($0.3<C_{eq}<0.5$), which implies that it is possible to obtain good quality welded joints with preheating and potential post-welding heat treatment.

2.1.2. *Preheating temperature*

The method for determining the preheating temperature by Seferian gives the following equation (1):

$$T_p = 350\sqrt{[C]-0.25}\ [^\circ C] \qquad (1)$$

where T_p represents the preheating temperature, while C represents the carbon equivalent of the base metal.

The calculated preheating temperature is 236 ˚C. Hence, the preheating temperature of 250˚C was adopted. Preheating was performed on-site using a gas burner. Due to this material's tendency towards cold cracking, the interpass temperature during the welding should remain between 150 – 300°C. In addition, the material needs to be covered in fireproof blanket, in order to ensure slow cooling, for reasons mentioned above. Preheating is a very important part of material preparation before welding, since the consequences of its inadequate application can be serious [14, 15].

2.2. Filler material

The selection of filler material is performed based on the quality and dimensions of the base material, complexity of geometry and the required quality level of the welded joint, as well as the welding position and procedure. The electrode chosen as the filler material was EVB Mo of Jesenice manufacturer [16], mainly due to its availability and sufficiently similar mechanical properties.

EVB Mo is an alloyed basic electrode containing molybdenum and it is meant for welding of steels with working temperatures up to 550°C, as well asfor non-alloyed steels with tensile strength up to 640 MPa. For an element thicker than 20 mm (such as the element discussed here) preheating is recommended.The chemical composition and mechanical properties of the EVB Mo electrode are given in tables 3 and 4.

Table 3. Chemical composition of electrode EVB Mo [%].

Electrode	C	Si	Mn	Mo
EVB Mo	0.08	0.45	0.95	0.5

Table 4. Mechanical properties of electrode EVB Mo (weld metal).

Electrode	Yield stress, $R_{p0.2\%}$ [MPa]	Tensile strength, R_m [MPa]	Elongation, [%]	Toughness (J)
EVB Mo	460-530	570-640	22-28	100-160

3. Welding procedure

The welding procedure was selected based on the following factors:

- Equipment potential of the contractor
- Human resources (welder competence)
- Welding activity cost
- Welding productivity
- Required quality of performed work

Based on the above factors, the manual arc welding procedure shielded metal arc welding (SMAW) was selected, using a coated electrode for the entire welded joint. This procedure can be used in all position, for all groove dimensions and shapes. Base metal preparation for the welding process consists of grooving and cleaning of the base material and reinforcement plates. This was performed in three stages: first stage involves penetrant testing and determining of the exact locations of potential cracks, for both forks (left and right); during the second stage, grooving is performed and penetrant testing was once again performed in order to check if the crack was eliminated. After this, the third stage takes place and involves the positioning of reinforcements on the lateral sides, if there is a possibility to perform this without affecting the functioning of the forklift. This is shown in figure 1,respectively the geometry and position of the welded joints between the reinforcement plate and the fork are shown in figure 2. All dimensions of figure 2 are given in millimeters, including the plate thickness and weld throat.

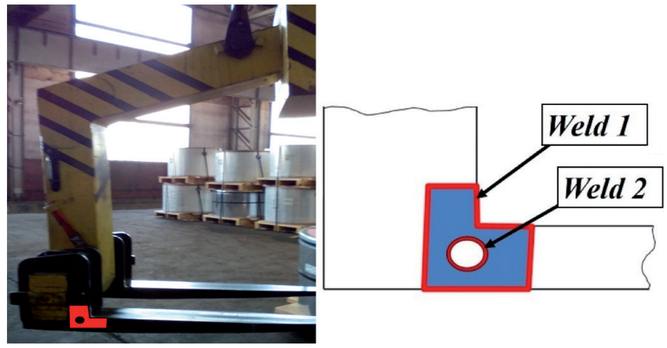

Figure 1. Reinforcement plate position on the forklift – the forklift structure (left) and the detail of the plate with welded joints (right).

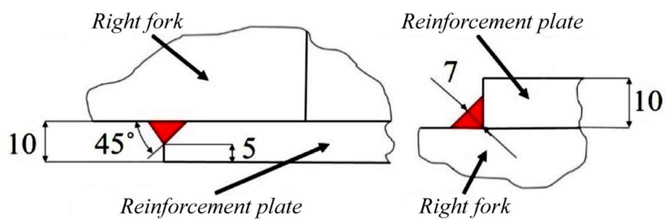

Figure 2. Geometry and position of welded joints between the reinforcement plate and the fork (in mm).

Welding parameters are given in table 5.

Table 5. Welding parameters.

Electrode diameter (mm)	Ø3.25	Ø4.0
Amperage (A)	110-140	140-170
Polarity	DC-RP (+)	DC-RP (+)

4. Control and inspection

4.1. Control after welding

Testing needs to be applied to each stage of welding, as well as to activities performed before and after it. The materials and welds can be examined and either accepted, rejected or repaired, depending on the size of the discovered defects.Methods used for examination of welds are known as non-destructive test methods or techniques (NDT). Also NDT techniques can be used to monitor the integrity of the element or structure throughout its design life [17].

In this case, testing was performed in three stages: testing prior to welding, testing during the welding, and testing after the welding. Visual-dimensional testing was performed in all three stages, liquid penetrant testing only after all welding activities were finished. Testing was performed after one month of exploitation, and then, repeated after three months, both visual-dimensional and liquid penetrant testing.

In order for the testing before the welding to be performed adequately, it is necessary to analyze the documentation about the quality of both the base and filler materials and, as a part of the visual-dimensional testing, to check if the grooves were properly dimensioned and cleaned. In this case, preheating is also an important factor to consider during the testing stage, mainly due to the base material tendency towards the forming of brittle phases, i.e. cold cracking.

The final stage of testing, which takes place after the welding activities have been completed, is also the most important stage in this case. This stage always involves 100% visual testing, and for the material used in this case, penetrant testing was also performed (100%). The revealed defects are classified according standards, depending on the required welded joint quality [18-20].

In the case of the forklift examined here, visual and penetrant testing revealed no cracks, on either of the forks. After the testing was performed, the forklift was returned to exploitation, however there was still a need to perform additional testing, due to the exploitation conditions, the location where the crack occurred and the way in which it initiated.

4.2. Control and inspection after one and three months in exploitation

After one month of exploitation, inspection detected a crack at the same welded joint which was previously repaired, but on the opposite side of the weld relative to the reinforcement plate. Visual inspection did not reveal the presence of the crack that was detected by penetrant method. The location of the crack, along with its appearance after the penetrant testing, can be seen in figure 3. The crack is denoted by the blue frames.

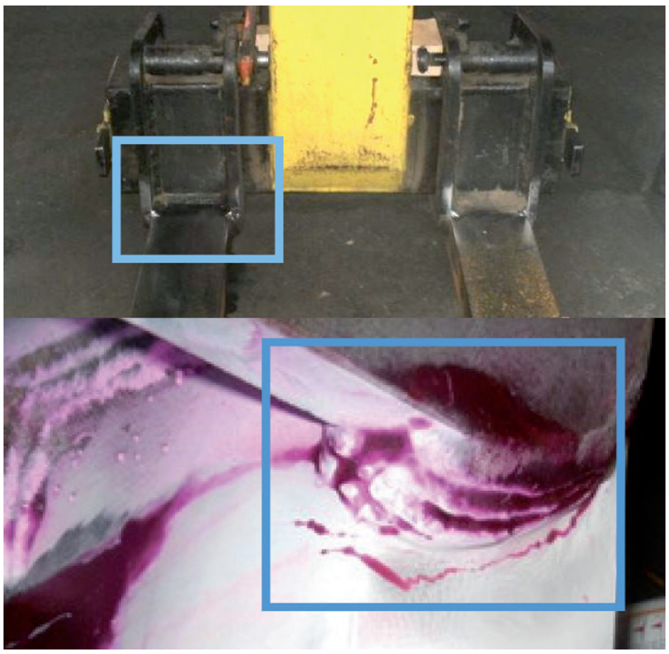

Figure 3. Position (left) and appearance (right) of the crack on the right fork.

The crack along with the whole weld were completely removed with machining until the base material was reached, and the fork was repaired using the same technology as before. There were no cracks observed in the left fork, according to visual testing, whereas penetrant testing detected a short crack which was not repaired. Instead, its behavior was closely monitored.

After three months of exploitation (two months after the previous testing), forks were once again inspected in detail, using visual and penetrant methods. Visual monitoring of the short crack in the left fork, which was not repaired, did not reveal any new cracks, or any growth of the existing one. Visual testing of the right fork did not reveal any new cracks. With penetrant testing, new cracks were revealed in the locations that were already repaired, as shown on figure 4.

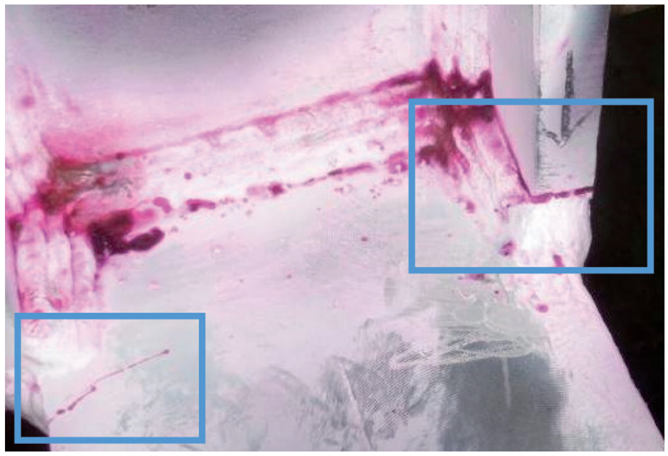

Figure 4. New cracks on the right fork, framed with blue squares.

5. Discussions and conclusion

This paper has presented the repairing of a forklift, which was performed twice after cold cracks were detected in the welded joint of the right fork. Even though both repair procedures were performed adequately, according to the relevant standards and regulations, cold cracks continually re-occurred around the welded joints. The following conclusions were reached based on this:

- The cold cracks were, in all likelihood, initiated due to residual stresses, which were caused by inadequate preheating during the manufacturing stage, i.e. before the forklift structure was assembled. This was particularly prominent in the case presented here, since the base material used, steel C45 had a strong tendency towards cold cracking, due to its high carbon content. As a result, a new crack continued to initiate in the base material near the welded joint, due to a combination of exploitation conditions and residual stresses resulting from inadequate preheating.
- Previous bullet also implies the possibility of cold cracks being present in other locations, outside of welded joints, which were not inspected using visual and penetrant test methods.
- The final conclusion was that the fork in question cannot be fully repaired, as the cold cracks will keep re-occurring, due to causes which cannot be fixed by repair welding, as these causes were present long before the fork was welded to the structure itself. This confirms the fact that sometimes it is not possible to eliminate "errors" from the designing and manufacturing processes, like the crack on the fork in the question. Remaining possibility for this equipment represents monitoring of the crack, until it reaches critical length.

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Calendar of International Events

2021			
07-21 Jul.	THE 74th IIW Annual Assembly and International Conference	online	https://iiw2021.com/
25 - 28 May	Young Professionals International Conference on Welding and Related Technologies	Kyiv, Ukraine	www.ypic2021.com
09 -10 March	6th International Electron Beam Welding Conference	online	https://www.dvs-ev.de/iebw2021/