Optimized welding processes for the repair and strengthening of structures made of old mild steels

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Abstract

When repairing or reinforcing existing structures made of old mild steel, the preferred joining method may be welding rather than bolting, as is usually the case. Due to the specific properties of old mild steels, special problems have to be considered. The weldability of old mild steels is particularly influenced by their highly scattering chemical composition, existing inclusions and their distribution in the component as well as their limited material toughness.

The first results of a research project at the Dresden University of Applied Sciences concerning the weldability of old rimmed mild steels have already been presented at Eurosteel 2017. This paper presents the findings of continued investigations, e.g. the use of other filler materials or out-of-position welding. The welding parameters were adjusted so that the toughness of the HAZ is better than in the unaffected base material.

Additionally, the suitability of flux-cored wire welding of old mild steels was investigated. This welding process enables a more economical production of large seam lengths. Unfortunately, the realized process parameters are very stringent, as the higher energy density of this process quickly leads to coarse grain formation in the HAZ and thus to a reduction in toughness.

Keywords

Construction in existing buildings, Repair, Reinforcement, Rehabilitation, Weldability, Old mild steels, Rimmed steels, Manual metal arc welding, Material toughness

1 Introduction

Although many structures made of old mild steel erected in the period between 1890 and 1940 are still under load after decades of service, there is usually no need to replace them. The large stock of older, generally operative steel structures requires their reuse in line with the demand for sustainable use of resources. As an example, the following three types of structures are in operation in large numbers and, due to their age, can be classified as mild steel structures. About one quarter of the bridge stock of the Deutsche Bahn AG are steel bridges. The average age of these bridges is 85 years. Therefore, a large number of the structures are built with old mild steels. Almost half of the steel lock and weir gates in the German federal hydraulic engineering facilities are at least 80 years old and thus originate from the above-mentioned years of construction. The same probably applies to several 10,000 steel lattice towers in the German power grid. A similarly large building stock exists in many other European countries.

An essential aspect of maintenance, rehabilitation and strengthening concepts for such, mostly riveted structures made of old mild steel are efficient joining methods. Currently, bolted connections with fitted bolts are used almost exclusively. Parallel to the enormous effort producing these fitted connections, the additional perforation leads to a further weakening of the cross-sections to be reinforced, especially in the case of tensile-stressed components.

2 State of the art

While puddle iron (wrought iron) generally has only a very limited weldability (see [1, 2]), welding of old mild steels is possible under certain conditions. Welded joints cause notch effects and residual stresses. This also increases the risk of brittle fracture. Compared to current structural steel grades, however, old mild steels have limited toughness. In order to minimize the risk of brittle fracture, e.g. in [3, 4] it is recommended to avoid welded joints in old steel structures as far as possible. The metallurgical specifics of old steels have to be considered if load-bearing welded joints are to be made nevertheless (see also [5, 6]). Significant parameters are the content of impurities in the segregation zone and the nitrogen-induced ageing of converter steels (Thomas and Bessemer steels). Systematic investigations of the weldability of mild steels have already been carried out in [7]. The focus was on fillet welds on the component surface of rimmed steels. The fusion penetration of the seams was technologically limited so that only the very pure rim layer and not the segregations were melted. Load-bearing and brittle fracture resistant welded joints of old mild steels could be realized.
Within the framework of individual documented rehabilitation measures on old steel structures (see [5, 8]), it was also shown that butt welding of old mild steels is possible despite the melting of the contaminated segregations. In these cases, however, the weldability of all components had to be tested in extensive material tests, in process tests and test welds on the structure and confirmed as approvals in specific cases. Experience and systematic investigations on a reliable scale, general process qualifications and normative regulations for welding old steels have not yet been available.

3 Initial experimental studies on weldability

The first results of an extensive research project concerning the weldability of old rimmed mild steels have already been presented at EUROSTEEL Conference 2017 [9]. Butt welds with double-V groove were produced on various old mild steel samples (see Table 1). Initially, welding was carried out in flat position (PA) using manual metal arc welding with thin basic-coated stick electrodes. The filler material reduced the tramp elements and provided ductile welds. The weldability of the examined old mild steels could be verified despite high concentrations of tramp elements in the segregations.

Up to the 1930s, steels were almost exclusively produced as rimmed steels. Therefore, the analysis by means of optical emission spectrometry (OES) was carried out on the cross-section of the components. Thus the segregation zones and rim layers were included in the measurements (see Figure 1).

The strength of the welded joints was determined on flat tensile specimens arranged transversely to the weld. All tensile test specimens exclusively failed in the base material of the old steel. Consequently, no significant weakening of the weld due to impurities or in the HAZ occurred.

4 Optimisation of the welding process for welding old mild steels

4.1 Impact on weldability due to different tramp elements

An important argument for the limited weldability of old structural steels is the excessive concentration of tramp elements, especially sulphur, phosphorus and nitrogen, according to current material standards. Sulphur generally reduces the material toughness and causes a marked anisotropy of the toughness values. This toughness anisotropy is caused by easily deformable MnS inclusions, which are elongated parallel to the surface after the rolling process. Due to the stoichiometric composition of manganese sulphides, a Mn/S ratio of at least 1.72 is required for chemical binding of the sulphur by manganese. If this ratio comes below the minimum value, an increasing proportion of the sulphur is bound as iron sulphide. This can lead to grain boundary coating of the sulphide and thus to hot cracking during welding. In order to avoid hot cracks and to compensate the reduction of manganese by absorption into the iron matrix, the Mn/S ratio should not be less than 4 [10]. Despite the high sulphur content, this minimum manganese content is present in all the mild steels investigated (see Table 2).

Phosphorus is considered to be a much more dangerous tramp element. It causes a significant deterioration of the toughness properties. This embrittlement is due to a decrease in cohesion, i.e. the grain boundary surface energy, as a result of phosphorus deposition [11]. With the increase in grain boundary area, i.e. grain refinement, the embrittlement effect of phosphorus should therefore decrease.

Like sulphur and carbon, phosphorus favours the formation of segregations in rimmed steels. If the segregation zone has to be melted during welding, the use of basic stick electrodes allows to largely slag the phosphorus in the weld metal due to the high calcium content in their coating.

In contrast to phosphorus, nitrogen causes time-dependent embrittlement in the steel, which is known as ageing. The ageing processes are caused by precipitation from supersaturated solid solutions. The excess nitrogen is deposited on lattice defects on its way to the grain boundaries during these diffusion processes. While this process progresses relatively slowly under natural conditions, it is accelerated considerably by the effect of heat, as during welding.

Table 1 Chemical composition of the material samples

| Material sample (year of fabrication) | Results of chemical analysis [%] (rim layer - segregation of I-sections) |
|---------------------------------------|---------------------------------------------------------------|
| MV (1888)                             | C 0.07  Si 0.008  Mn 0.51  P 0.069  S 0.103  Al 0.002  N₂ 0.0170  O₂ 0.0259 |
| GDD (1890s)                           | C 0.08  Si 0.008  Mn 0.44  P 0.074  S 0.032  Al 0.004  N₂ 0.0175  O₂ 0.0322 |
| HDD (1913)                            | C 0.07-0.12  Si 0.002  Mn 0.63-0.85  P 0.06-0.12  S 0.07-0.14  Al 0.001  N₂ 0.0250  O₂ 0.0155 |
| AV (1878)                             | C 0.07  Si 0.004  Mn 0.42  P 0.057  S 0.084  Al 0.003  N₂ 0.0210  O₂ 0.0361 |
| TFT (1920s)                           | C 0.04-0.07  Si 0.001  Mn 0.43-0.60  P 0.05-0.15  S 0.03-0.12  Al 0.001  N₂ 0.0200  O₂ 0.0291 |
| TFS (1920s)                           | C 0.04-0.06  Si 0.006  Mn 0.46-0.51  P 0.04-0.09  S 0.01-0.02  Al 0.002  N₂ 0.0140  O₂ 0.0196 |
This effect must be taken into account especially in the case of converter steels (Bessemer and Thomas steels), since the solubility limit 0.014% of nitrogen is often exceeded [12].

4.2 Impact of welding technology on the microstructure

The changes in grain structure in the HAZ due to the introduced heat were quantified by grain size determination according to DIN EN ISO 643. Figure 2 shows characteristic grain distributions in the HAZ of three weld samples of the materials TFT (a), AV (b) and MV (c). Clearly visible is the reduction in grain size from the base material to the weld seam. The reduction in grain size is also clearly visible from the number of ferrite grains N in the test grid and the increasing grain size number G. No marked coarse-grain formation near the fusion line occurred.

The chemical composition of the steel, the heat input and a possible preheating temperature have a decisive influence on the grain size in the HAZ of a mild steel weld. Coarse-grained microstructure causes a number of significant disadvantageous steel properties. According to the Hall-Petch relation (see [11]), strength and toughness decrease with increasing grain size. In addition, the tendency to re-melting cracks increases, as the smaller grain boundary area increases their density of impurities.

The multilayer technique (stringer bead or weave bead technique), which was used for the welded joints investigated here, has a strong quality improving effect. In contrast to the single-layer technique, the microstructure of the underlying layer(s) of the weld metal as well as the HAZ is subjected to marked refinement due to the double recrystallization during heating and cooling (α ↔ γ). The significantly lower heat input of the individual layers significantly reduces the width of the HAZ and the grain size in the coarse-grain zone compared to the single-pass technique. The cooling speed is reduced by the “preheating effect” of the individual layers. It is, however, considerably higher than with single-layer butt welds. This prevents excessive grain growth. As a result, there is a continuous reduction in the grain size of the base material up to the fusion line. The average grain size number G in the HAZ of 8 to 9 (see Fig. 2) corresponds approx. to that of the new structural steel.

The described image series analyses were carried out at the level of the cover beads in order to exclude the multiple microstructure transformation in the HAZ by repeated heating. Furthermore, the material quality in this area of maximum geometric notch effect through the weld seam is of primary interest. Additional investigations in deeper layers have shown that the coarse-grain zone can be completely eliminated by multiple “re-graining” on the flank of the multi-layer weld. Therefore, strength and toughness increasing effects can be expected in the HAZ of the old mild steel.

4.3 Impact of welding on the material toughness

Initially, the transition temperatures $T_{27}$ for the unaffected base materials were determined in Charpy impact tests to assess the toughness of the material in the welded joint. In comparable investigations (see [13]), the transition temperature of old mild steels was approximately in the range of 0 to +40 °C. To determine the transition temperature, two sets of Charpy impact test specimens (3 each) were analysed in this temperature range. The first three impact tests were carried out at room temperature (about 20°C). If the mean impact energy of these three tests was more than 27 J, the analysis of the following three samples was carried out below 20°C, otherwise above. The transition temperatures $T_{27}$ was determined by interpolation and amount to values between -3°C and +45°C. Thus, the investigated materials represent the typical spectrum of old mild steels.

Subsequently, the impact energy of the samples from the corresponding HAZ was determined at these temperatures. In some cases, the tests yielded similar, but usually significantly higher toughness values than in the unaffected base material (see Fig. 3). Thus, the test results confirm the findings on improving the material quality from the metallographic examinations (see section 4.2).

When refurbishing and strengthening existing steel structures, sometimes, due to the design, only one-sided weld preparation is possible or the joint is only accessible from one side. Therefore, welding test specimens with single and double bevel groove were examined in the same way like the specimens with double-V groove.

Figure 2 Typical grain size in the HAZ over fusion line (left) to basic structure (right). Source: HTW Dresden
The iron nitrides produced by segregation processes degrade during welding in the zones heated above 620°C (see [14]). Thus, the embrittlement due to ageing is reversed. It can be assumed, however, that the ageing process starts again after welding due to the increased nitrogen content in the old converter steels and the toughness decreases again. In order to assess the influence of repeated ageing on the ductility of the welded joints, additional investigations were carried out on artificially aged samples. For this purpose, several weld specimens of different materials were aged for 1 h at 250°C. This heat treatment favours the segregation processes of nitrogen and accelerates the ageing process of the steels. However, it is known from the investigations in [14] that this method leads to more intensive embrittlement than occurs under natural conditions.

Charpy impact test specimens with notch in the HAZ of the old steel were fabricated and analysed. The results of the impact tests on the aged specimens are shown in Figure 4. Obviously, the average toughness of the HAZ decreases due to ageing but it is still significantly higher than in the unaffected base material.

### 4.4 Suitability of Old Mild Steels for Out-of-position Welding

Based on the very conservative estimates of the weldability of old mild steels (see section 2), very favourable boundary conditions (double-V groove, flat position, thin electrodes) were selected for welding at the beginning of the described investigations. Welding details in real rehabilitation tasks often require out-of-position welding, for instance vertical upwards. For this reason, samples with vertical butt welds (double-V groove) were produced and analysed in a further investigation stage.

For technological reasons, vertical weldseams must be welded with low welding current intensity in order to achieve rapid solidification of the weld metal, which is additionally braced by the slag. In some cases, this can lead to the inclusion of pores or wormholes, e.g. if there are cavities or outgassing inclusions at the seam flank [15]. Therefore, it is recommended to inspect the welds to prevent such defects, especially in the case of highly contaminated mild steels.

In contrast to welding in flat position, vertical seams must be welded using the weave bead technique instead of stringer beads. This leads to a significantly higher heat input and thus to slower cooling (see Section 4.2). In order to intensify the test conditions and further increase the heat input, basic electrodes with a core wire diameter of 3.25 mm were used for the intermediate and cover layers. As a result, the energy per welding layer was about three times higher than at the welds in flat position.

The metallographic examinations of these welds showed that a coarse-grained zone in the HAZ was formed due to the higher heat input, mainly at the level of the cover layers. As a result, the average material toughness of these zones decreased in the Charpy impact tests. However, the toughness was still higher than in the unaffected base material. In the transverse tensile tests, the samples also failed in the old steel, far from the weld seam.
4.5 Suitability of other welding methods and filler materials for welding old mild steels

For welding of purer mild steels (lower phosphorus and sulphur content) basic-rutile coated electrodes (e.g. Kjellberg GARANT BR, OPTIMAL or similar) can also be used. They can be welded at the “cooler” positive terminal just like the basic electrodes. Thus the heat input into the old mild steel is limited. In welding tests, similarly good material properties have been achieved. In addition to easier processability, these electrodes can be used to produce smoother seam surfaces with a notch-free weld transition. During out-of-position welding, special attention must be paid to avoid pores and slag inclusions.

In addition to the very ductile weld metal, a significant advantage of using basic coated electrodes is the ability of the coating to bind and slag harmful tramp elements. If larger seam volumes or longer welds with similar quality have to be produced, metal arc welding using basic flux-cored wire is a suitable alternative process. This has been demonstrated in initial test welds on mild steel. On the one hand basic flux-cored wire T46 4 B M 3 H5 according to DIN EN ISO 17632 (here DT-BF 31 from DRATEC Company) was used. Since this can only be welded in flat position, test welds for comparison were also produced with a rutile flux-cored wire T46 P C/M 1 H5 (here Fluxofil 14HD from Oerlikon Company). This flux-cored wire is suitable for out-of-position welding as well as for use under construction site conditions.

Due to the higher energy per unit length in flux-cored wire welding, despite stringer bead technique and welding in flat position, the heat input is as high as in vertical seams welded with stick electrodes. This leads to an initial coarse grain formation and decreasing toughness in the HAZ (see Section 4.4). This effect could also be demonstrated on all seams welded with flux-cored wire, irrespective of the filler material used. In out-of-position welding (e.g. vertical, position PF), the welding speed in the intermediate and cover layers decreases for technological reasons. The heat input significantly increases. This leads to a marked coarse grain zone in the HAZ combined with a significant reduction of the material toughness of the old steel. Therefore, flux-cored wire welding is only suitable for long thin seams and welding in flat position or “rim layer welding” (see [7]).

5 Application examples

5.1 Rehabilitation of the buckled plates of a riveted road bridge

During the maintenance of the road bridge (built in 1894) in the Dresden harbour, after the removal of the road surface and the sealing, in some cases significant corrosion damage was found on the buckled plates underneath. In addition to a surface corrosion, the drainage holes at the bottom of the buckled plates were particularly affected. The rehabilitation design provided the installation of drainage pipes made of circular steel pipe for controlled water drainage. After blasting the corrosion-damaged components, it became apparent that almost half of the buckled plates were too badly damaged at the drainage holes for direct connection of the pipe sections. Here, pieces measuring approx. 40 x 40 cm were removed and replaced by new steel plates including drainage pipes.

Figure 4 Results of the Charpy impact tests on artificially aged samples. Source: HTW Dresden
As the bridge is to be used in future only as a pedestrian and cyclist bridge, the existing sidewalk was dismantled. The buckled plates of the dismantled structure were thus available for investigations of the weldability. Several test welds for the two described rehabilitation variants were produced and examined mechanically and metallographically (see Figure 5). As a result of the investigations, load-bearing and flawless welds were certified and the weldability of the old buckled plates was confirmed.

5.2 Rehabilitation of an impact damage at a railway bridge with concrete-encased steel beams

The impact of a transport vehicle on the Ritschenhausen railway bridge damaged the edge beam of the concrete-encased steel beams superstructure. As the steel girders of this historic superstructure (built in 1910) were only partially encased in concrete, an approx. 1 m long piece of the bottom chord was pulled down (see Figure 6). The rehabilitation design provided to replace the damaged lower chord with a T-section girder of similar dimensions. The connection by bolts was not possible due to an interfering reinforced concrete cross girder (see Figure 6). After chemical and metallographic analysis of the old steel material, the welding engineer decided to weld the new girder into the existing girder. In order to avoid unintended residual stresses due to the transverse shrinkage of the weld seams, only the end face near the crossbeam was butt welded. The connection of the opposite side was made after completion of the welding work by a bolted double strap butt joint. The weld seams were completely subjected to an ultrasonic test according to DIN EN ISO 17640, so that internal imperfections such as pores, wormholes or lack of fusion could be avoided.

Figure 5 Bridge with corroded buckled plates (left), newly welded drainage pipes (right). Source: HTW Dresden

Figure 6 Damaged edge beam after impact (left), repair by welding in a new T-section girder (right). Source: DB Bahnbaugruppe GmbH
6 Summary and conclusions

The presented results of the research project indicate that the possibility of welding old steels, which has already been described in the technical literature in individual cases, can obviously be used systematically for the materials investigated. The commonly predominant opinion of generally rejecting welding for these materials is not validated by the results of the project.

A conventional S235J2 or similar is sufficient as a joining material for repair or reinforcement measures. It is already better than the usual old mild steels in terms of weldability and toughness. If the following recommendations for welding are considered, the weld or HAZ does not represent a weak link and the typically lower strength of old steels is decisive for the assessment of the overall structure.

For structures with fatigue-relevant stresses, systematic investigations into fatigue strength are pending. It is obvious that the described favourable influences on the microstructure in the weld seam and HAZ do not have a less favourable effect on the fatigue strength than for normal structural steels.

6.1 Recommended material analyses to evaluate weldability

In spite of the predominantly positive results of the described investigations, no unrestricted weldability for old mild steels can be certified. Despite their unfavourable chemical compositions, the materials examined do not represent the entirety of mild steels from a manufacturing period of over 60 years.

In order to assess the weldability of a component made of old mild steels, the authors consider the following three investigations necessary:

1. Performing a chemical analysis (at least C, Si, Mn, P and S). It must be carried out on the cross section of the sample (not on the component surface) in order to analyse the segregation of the rimmed steels. It is also necessary to determine the nitrogen content, e.g. by means of carrier gas hot extraction. The following limit values are recommended for old mild steels suitable for welding.

\[
\begin{align*}
C \, [\%] & \leq 0.25 \\
P \, [\%] & \leq 0.08 \\
S \, [\%] & \leq 0.06
\end{align*}
\]

If the limit values are exceeded, the suitability for welding can be examined by specialists with expertise in this subject. The experience from the investigations presented in Section 4 may also allow welding in such cases.

2. Preparation of a non-etched longitudinal section (along the profile or rolling direction) to investigate slag formation and slag frequency. This may cause pores during out-of-position welding. Additionally, it influences a possible reduction of the load-bearing capacity in fillet welds perpendicular to the component surface due to lamellar tearing.

3. Preparation of a sulphur print on the transverse section (transverse to the profile or rolling direction) to determine the segregation zone and thickness of the rim layers near the component surface. These investigations are particularly important for the production of fillet welds on the component surface ("rim layer welding").

For these tests, a material sample has to be taken, e.g. by means of a core hole drill (sample diameter approx. 20 mm). Care shall be taken that the longitudinal or rolling direction of the component is marked on the sample. The specimen taking shall be performed on the part and in the cross-sectional area (e.g. edge of the flange) where welding is to be performed. If the welding task is not yet known in detail, the specimen shall always be taken in the most "weld-critical" part of the cross-section (e.g. the web of I-sections), since mild steels were almost rimmed steels until the 1930s.

6.2 Recommendations for the preparation and execution of the welding work

Depending on the particular welding task, the following recommendations should be taken into account when welding old mild steels:

- Removal of old coatings and any corrosion products (rust) in the weld area.
- Preheating the weld area to approx. 80°C before welding, e.g. with an oxyacetylene torch with shower head. If scattered corrosion pits remain after rust removal, the heating ensures that the moisture from these areas dries out and thus prevents hydrogen embrittlement of the weld seam.
- Re-dried, basic coated stick electrodes with a core wire diameter of max. 3.25 mm (2.5 mm for out-of-position welding) are to be used for welding. Basic coated electrodes are recommended so that only a small fusion penetration is achieved in the rim layers during welding. When welding in the segregations, these electrodes best bind and slag harmful tramp elements.
- Weld seams should always be produced in multi-layer technology (with stringer beads or, if necessary, weave beads) in order to minimise the internal stresses in the weld area and to realise grain refinement in the HAZ. The energy per unit length of the individual layers shall be limited to about 25 kJ/cm weld length to avoid coarse grain formation in the HAZ as far as possible.
- Butt welds shall principally be executed as full penetration welds. Double-sided butt welds shall be preferred to single-sided butt welds, if both sides of the joint are accessible. If the butt weld is single-sided (e.g. single-V groove in flat position), the weld root shall be removed by gouging or grinding and rewelded. The weld preparation is preferably performed symmetrically on both joining members, but at least on the side of the old steel in order to ensure a smooth material transition.
- As commonly known, no welding should be performed in the area of cold forming. Recrystallization of cold-formed parts in the temperature range around 650°C causes ageing effect in the usually highly nitrogenous old steels due to the precipitation of iron nitrides. This is particularly relevant in the area of rivet holes, plate edges and profile ends, since these were often produced by punching and shearing (see also [13]).

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