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D4.6.2 – Report on the Influence of the Working Procedures and Post Treatment on Static and Dynamic Fatigue Behaviour of Aluminothermic Welds

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Table of Contents

Glossary	2
1. Executive Summary	3
2. Introduction	4
3. Mechanical Treatment	5
4. Thermal Treatment.....	10
5. Conclusions.....	13

Glossary

Abbreviation/acronym	Description
HB	Brinell hardness
SkV, SkV-Elite	aluminothermic weld with optimized HAZ (German denotation: "Schnellschweißverfahren mit kurzer Vorwärmung")
UIT	ultrasonic impact treatment
σ_{\max}	upper load (maximum stress) during fatigue test
σ_{\min}	lower load (minimum stress) during fatigue test

1. Executive Summary

In the present report two post treatments of aluminothermic welds are described that can successfully be applied to improve the weld properties.

One of the influencing factors on the static as well as on the dynamic fatigue behaviour of aluminothermic welds is the quality of weld surface and design of the weld collar. Especially the transition from rail to weld collar needs to be taken into account. The presence of any kind of weld defects and notches at this transition can be the cause for fracture initiation and failure of the weld.

A mechanical post treatment of the weld (ultrasonic impact treatment) is available and it can be shown that the fatigue life of aluminothermic welds can clearly be improved. The mechanical deformation of the surface layers has a beneficial influence, but also a further effect on the microstructure in greater depths under the surface improves the fatigue life.

Changing selectively the microstructure of a component to effectuate a better performance of the weld is the purpose of the second method described in this report. A post heat treatment of the base of weld and rail can be applied to improve the bending properties of high strength rails. In the example given in the report it could be shown that the deflection during the slow bend test of full-hardened rails could noticeably be increased.

2. Introduction

The static behaviour as well as the dynamic fatigue behaviour of aluminothermic welds is – amongst others – determined by the quality of weld surface and design of the weld collar. Especially the transition from rail to weld collar needs to be taken into account. The presence of any kind of weld defects and notches at this transition can be the cause for fracture initiation and failure of the weld.

Not only notches or weld defects must be considered but also the microstructure of weld and rail material is important. The material properties such as yield strength, tensile strength and fracture toughness are determined by the chemical composition and the microstructure of the material.

The possibilities to have a direct influence on the properties of an aluminothermic weld are restricted as long as the welding procedure remains unchanged. Therefore only a post treatment of the finished weld is possible to improve the weld properties.

In this report two possible treatments will be addressed. A mechanical treatment of the transition from rail to collar in order to improve the dynamic fatigue behaviour and a thermal treatment of the weld base in order to improve the static behaviour.

Aluminothermic welding procedures complying with EN 14730-1 have in normal conditions sufficient static and dynamic fatigue behaviour. Only when better static and dynamic fatigue behaviour is needed a supplementary mechanical or thermal treatment can be used.

3. Mechanical Treatment

It is well known that the notch effect has a deteriorative influence on the fatigue behaviour. High stresses in front of the notch tip as well as high internal stresses must be considered if a dynamic load is additionally applied, and the local stress concentrations are often the reason for the failure of structural components under service conditions.

Critical locations of the weld that are susceptible to fracture initiation during dynamic load are the transition from rail to weld at the underside of the base and at the upside of the foot (transition from base to web).

The distribution of the residual stresses in the rail, their magnitude and direction varies depending on the production process. The residual stresses of rails in the as-rolled condition are different from rails that have additionally been heat treated. During aluminothermic welding the residual stresses will be changed again and residual stresses will be generated in the weld due to a different thermal expansion (and contraction) of rail and weld during and after the welding process.

Furthermore, the transition from weld collar to rail is discontinuous and it is possible that notches are generated during the welding procedure.

If a special mechanical treatment is applied to this transition from weld collar to rail the dynamic fatigue behaviour can be improved. This improvement is caused by the following main effects:

- A mechanical impact treatment of base and web (transition rail / collar) causes the formation of compressive residual stresses. A dynamic load of the rail effects a bending of the rail and results in a tensile load in the base of rail and weld. The presence of compressive residual stresses makes the applied tensile load less critical with regard to fracture initiation and fracture propagation.
- Secondly, the mechanical treatment of the surface represents a plastic deformation of the weld surface (strain hardening of the surface layers). Therefore, any kind of notches or irregularities on the surface can be smoothed to a certain extent. The presence of notches will therefore not be that critical as before because the notch effect will be reduced. However, an additional grinding of the surface is recommended in order to reduce remaining surface effects.

A pure surface treatment of the weld collar is possible by e.g. shot peening. Shot peening will change the stress conditions of the surface of weld collar and rail, and shot peening will remove surface irregularities. It is an approved method to improve fatigue properties.

An UIT procedure has been introduced in order to improve fatigue properties of aluminothermic welds. This ultrasonic impact treatment fulfils the above mentioned conditions, but during this treatment the frequency of the impacts has an additional effect. The vibrations that are induced in the metal causes a rearrangement of dislocations. Basically, this recovery process leads to a reduction of the dislocation density in larger depths of the material. Thus, it is possible to reduce the hardness of the material in those regions that are critical with respect to fracture propagation during dynamic load. In general, a reduced hardness is linked to an improved ductility of the material which has a positive influence on the fatigue resistance.

Figures 1 to 3 show the device that is used for the mechanical treatment (ultrasonic impact treatment) of weld collar at the transition from collar to rail (Figure 1: treatment of the transition from base to web; Figure 2: treatment of underside of base; Figure 3: treatment of upside of the foot). In **Figure 4** the running surface of the rail can be seen directly after the impact treatment.

These figures given below also reveal the technical limitations of the impact treatment. As long as fatigue properties of the welds are investigated on a laboratory scale it is possible to apply this technique on the upside of the base and on the bottom side of the foot. If this technique should be applied during the installation on-site only the treatment on the topside of the foot is possible. It is hardly possible to have an adequate access to the bottom side of the weld. Nevertheless, it is assumed that the penetration depth of the

ultrasonic waves is sufficiently high to have an improving influence through the complete base and foot of the rail.

Furthermore, Figure 3 and Figure 4 show clearly that the surface is plastically deformed during the impact treatment. As mentioned above, the surface that has been treated with this technique should be grinded afterwards to avoid any further disturbing influences.



Figure 1 *Impact Treatment of Weld Collar (Transition Base to Web)*



Figure 2 *Impact Treatment of Weld Collar (Bottom Side of Weld)*

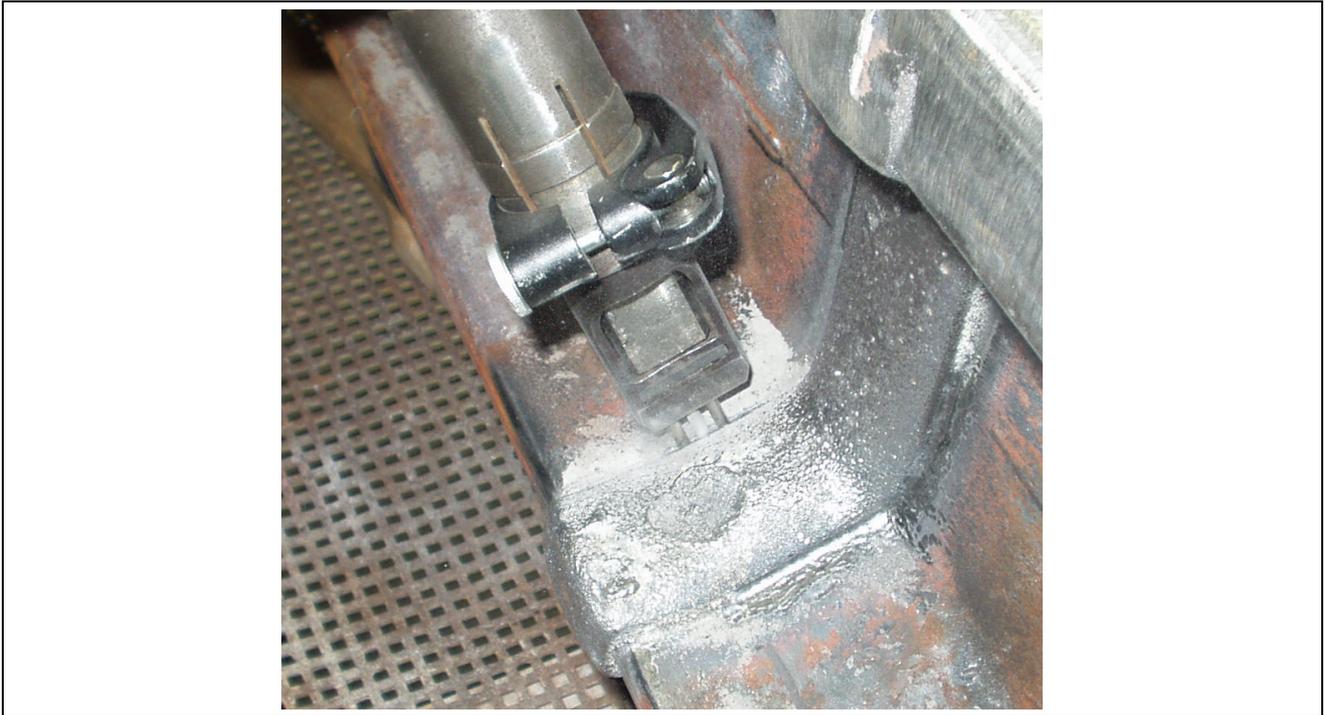


Figure 3 *Impact Treatment of Weld Collar (Upside of Foot)*

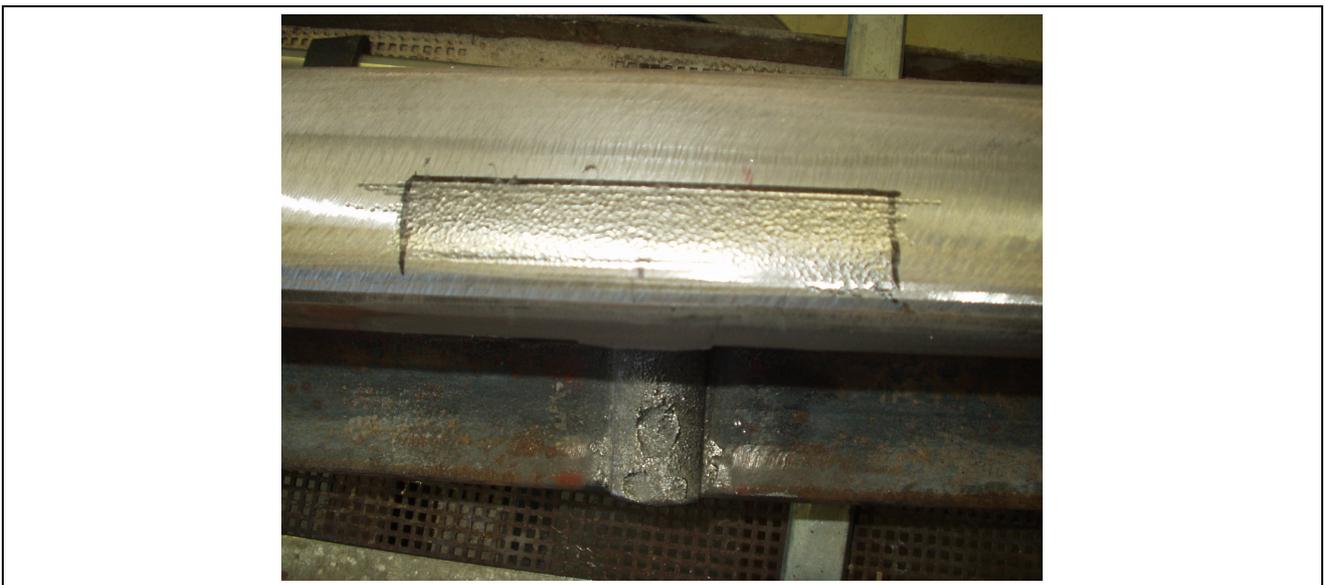


Figure 4 *Impact Treatment of Running Surface*

The ultrasonic impact treatment has been introduced to improve the fatigue properties of aluminothermic welds. A couple of fatigue tests on welds that have been treated with UIT have shown that the number of load cycles before break of the specimen can clearly be increased.

In **Table 1** a listing of the test results is given, **Figure 5** gives a graphical representation (in ascending order).

Table 1 Results of Fatigue Tests, Number of Load Cycles N

test no.	without impact treatment	with impact treatment
1	358.200	1.896.600
2	413.100	2.239.200
3	508.300	2.508.900
4	587.300	3.193.100
5	623.500	3.903.300
6	776.000	5.300.000
7	1.075.800	–
8	1.966.300	–

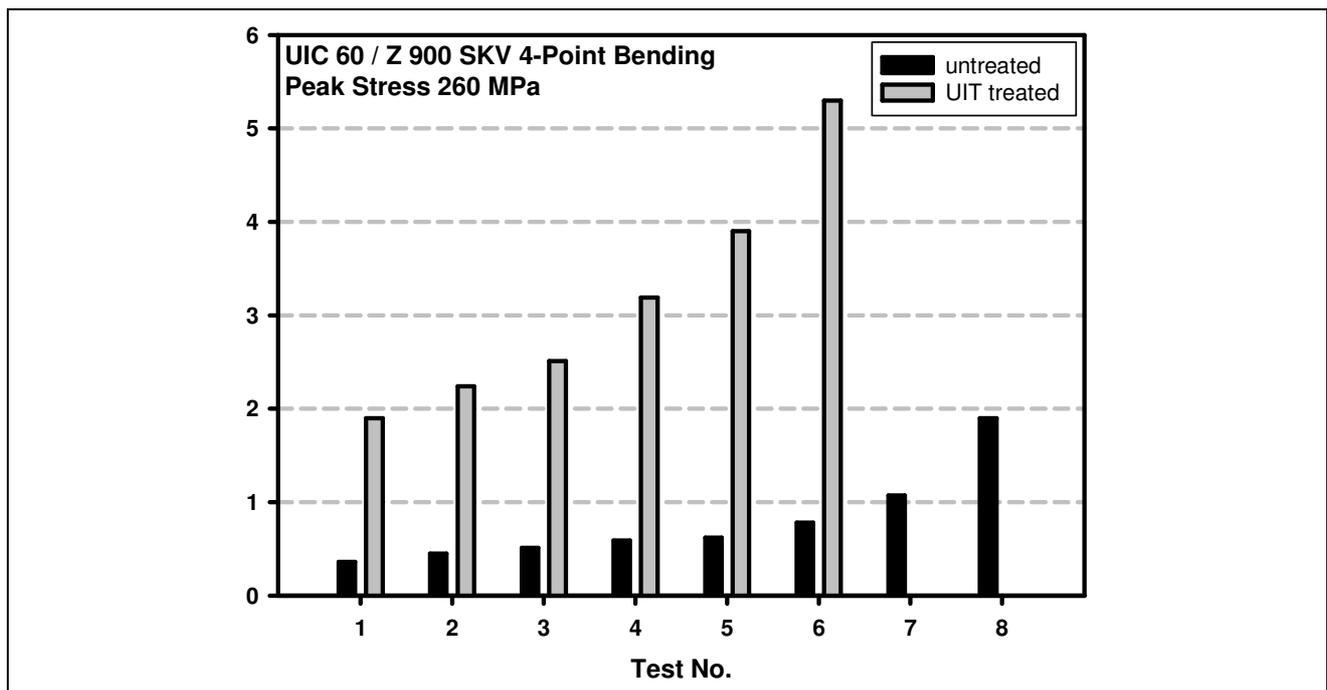


Figure 5 Results of Fatigue Tests, Number of Load Cycles N (·10⁶)

The above given results have been achieved on 60E1 rails of grade R260. The aluminothermic weld joints were welded using the welding procedure SkV-Elite. The fatigue tests were performed using the 4-point bending technique (upper load: $\sigma_{max} = 260$ MPa, lower load: $\sigma_{min} = 26$ MPa).

The results show that the number of load cycles before fracture of the weld (impact treated) can be improved by a factor of about 5.

Figure 6 and 7 show the corresponding Weibull distributions of the achieved fatigue test results. The Weibull distribution serves a statistical device to analyse failure rates. Here it can be seen that the probability of failure is clearly decreased if the impact treatment is applied (blue curve, Figure 6, compared with black curve, Figure 7). The curve in Figure 6 indicates that two different failure mechanisms are active as long as no impact treatment is applied (two different slopes). The red curve (Figure 7) represents a linearization of the initial concave curve (black) by subtracting a constant value t_0 . This linearization indicates that a life cycle t_0 exists where no failure of the weld occurs. (T is the characteristic life cycle (probability of failure 63.2%); b is a parameter indicating the slope of the graph in the Weibull diagram).

The given statistical evaluation is based on a few test results only. In order to reveal the full potential of the ultrasonic impact treatment a more statistical basis is required.

Nevertheless, it is undoubted that an improvement of fatigue properties is achieved if the weld is treated by the ultrasonic impact treatment.

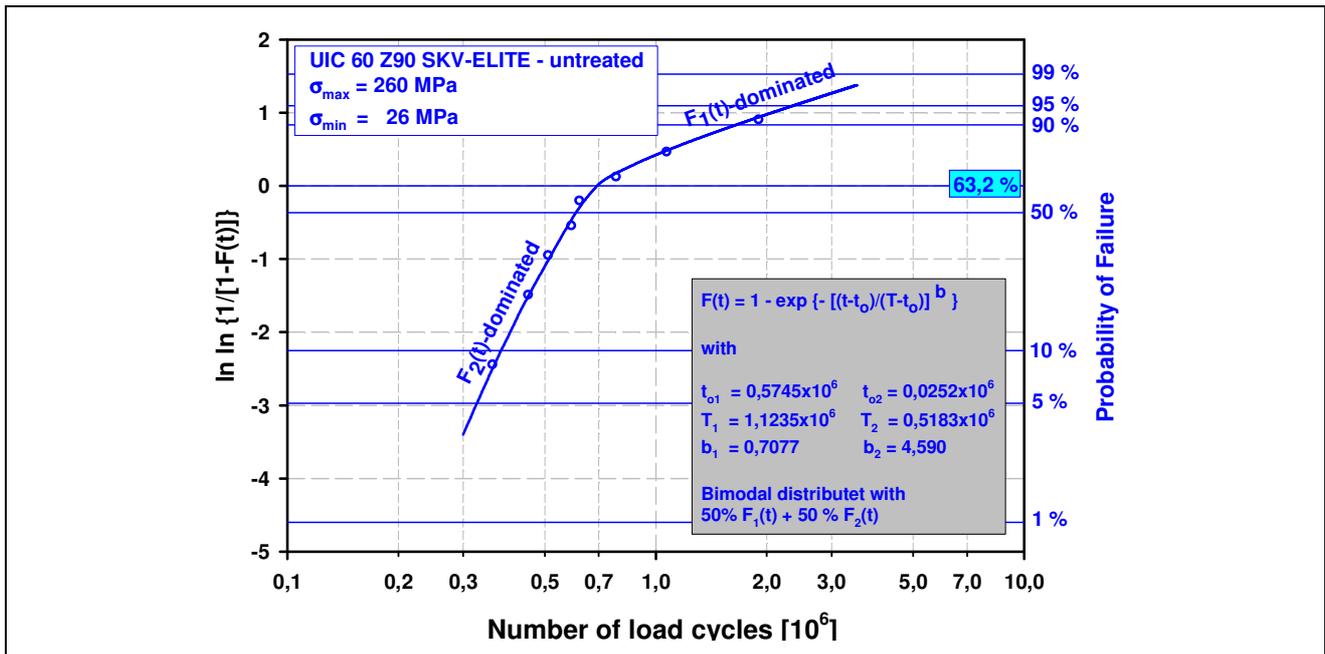


Figure 6 Weibull Distribution of Fatigue Test Results – Untreated Welds

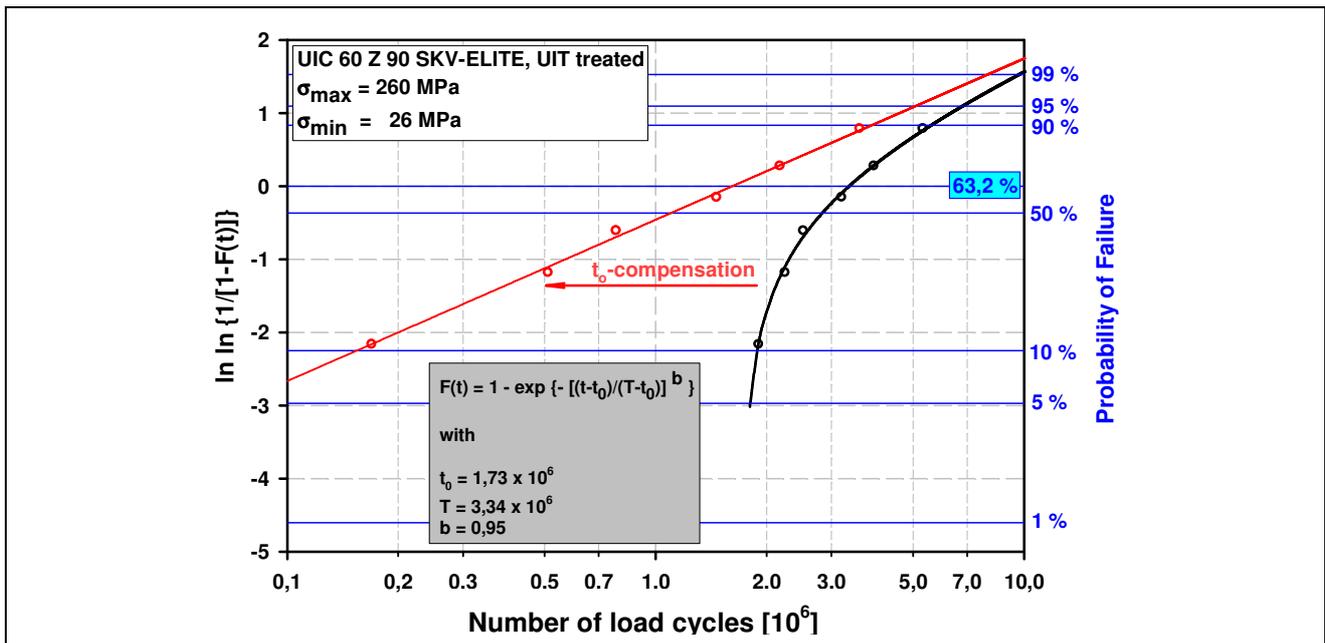


Figure 7 Weibull Distribution of Fatigue Test Results – Impact Treated Welds

4. Thermal Treatment

A heat treatment of metallic materials always has the aim to influence the microstructure of the material and consequently to modify the mechanical properties. Depending on the initial condition of the material, the chosen annealing temperature and the chosen annealing time the result will be different. For example, recovery and recrystallisation of plastically deformed metal can be a result of an annealing process. Phase transformations will be observed if reaching the corresponding transformation temperatures (during heating or cooling).

However, microstructure will change if the material is exposed to higher temperatures.

In the case of aluminothermic welds one could think of two main possibilities to change the microstructure and to improve the properties of the welds by means of an additional post heat treatment. On the one hand it is possible to anneal the rail head and on the other hand it is possible to anneal the base of the weld. The first solution results in a formation of a fine grained ferritic-perlitic microstructure on the running surface, presuming that the corresponding aluminothermic welding procedure and thermit portion have been chosen. The second solution simply results in a softening of the material in the weld base due to the annealing treatment.

Basically, both procedures have the same intention. The head of the weld or the running surface has a comparably high hardness and the base and foot of the weld will become comparably soft. The high hardness of the running surface is desirable in order to improve the resistance against rolling contact fatigue. A soft base of the weld will make the material more ductile so that the bending strength and the bending fatigue properties will be improved.

In the following the improvement of the bending properties will be shown exemplarily on R65 rails with a hardness of about 350 HB. The investigated rails are not head hardened but mainly full-hardened. The aim of the investigation was to ensure a deflection of 20 mm minimum during the slow bend test.

The underlying problem is that aluminothermic welds with high hardness don't have a high capacity to bear high amounts of plastic deformation and a deflection of 20 mm is difficult to be achieved without any further arrangements.

Furthermore, the available welding processes are strictly defined and cannot be modified arbitrarily. Therefore, it is primarily necessary to choose the correct grade of the thermit portion and a suitable welding procedure. In the given case it was decided to use SkV as welding procedure and Z120 portions (350 HB).

Experience and a couple of pre-tests have shown that the attempt to use portions of a lower grade to increase the deflection during the slow bend test was not successful. The usage of a soft portion does not automatically imply that high amounts of plastic deformation can be reached in the given constellation "hard rail / soft weld / hard rail". The deformation will be localized in the soft weld. A deflection of 20 mm or higher cannot be achieved by a plastic deformation solely in the weld.

Consequently the grade of the thermit portion needs to be same as the grade of the rail in order to have a uniform deformation along the complete weld joint. Nevertheless, the SkV welding procedure (using Z120 portions) only led to deflections of about 10 mm (see **Table 2**).

The aim to reach 20 mm deflection can therefore not be attained by the chosen welding procedure without any additional efforts.

As already mentioned above, a tool has been developed that permits a selective heat treatment of the rail foot. This heat treatment is conducted 11 minutes after tapping started for a period of 11 minutes. These parameters had been determined during the development of the complete heat treatment procedure and the corresponding equipment and had been found to be suitable for the R65 rail profile.

Figure 8 and **Figure 9** show the burner for the heat treatment of the rail foot.

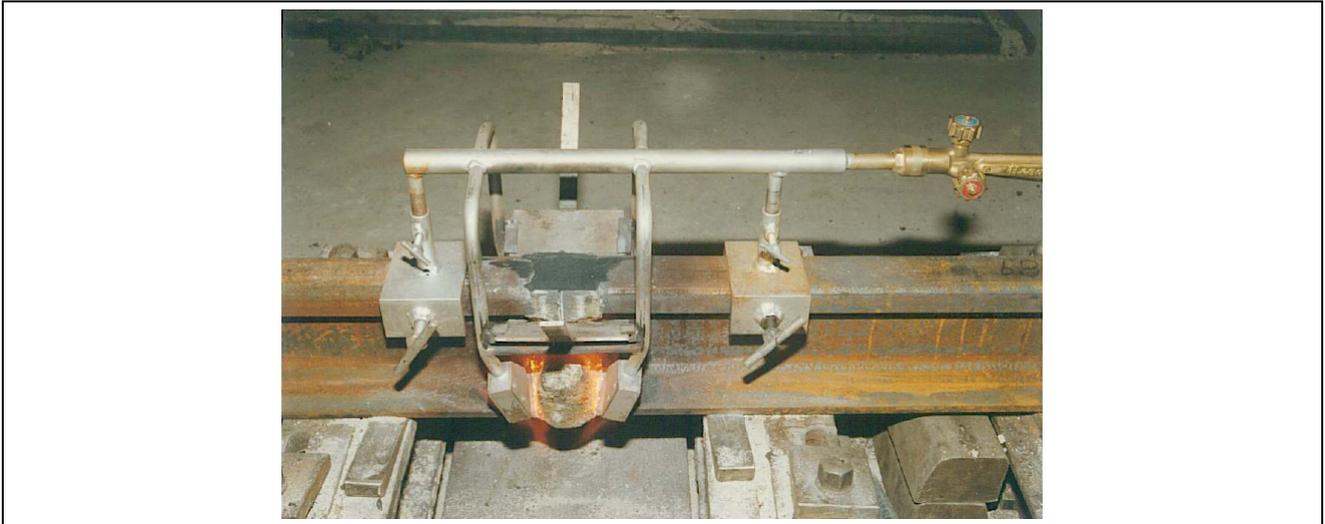


Figure 8 **Burner for Heat Treatment of Rail Foot**

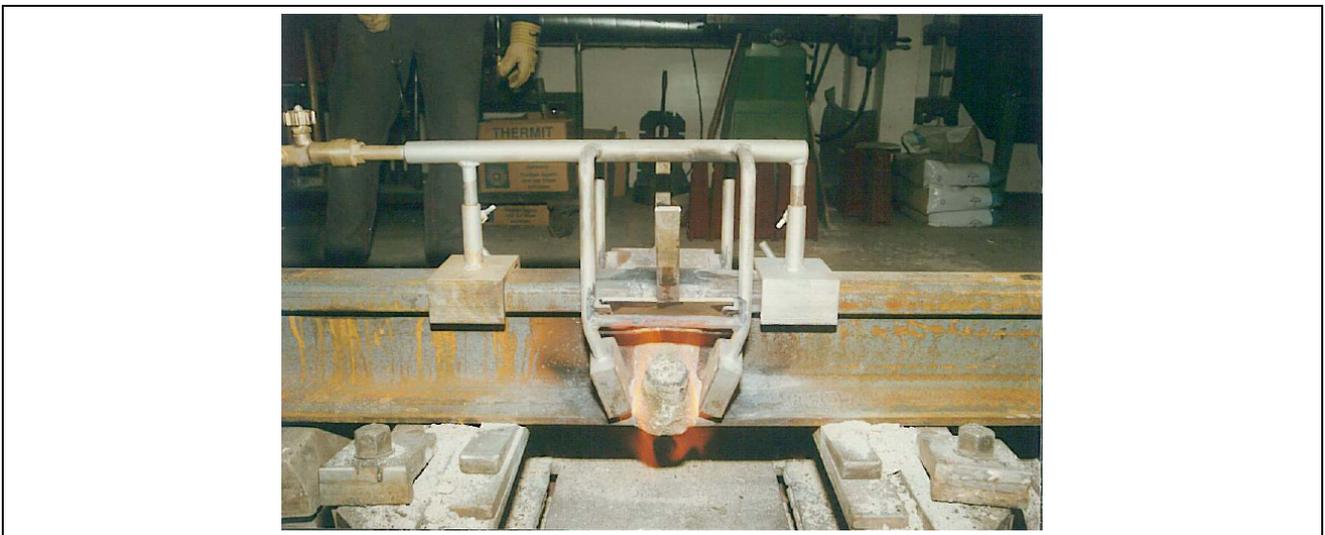


Figure 9 **Burner for Heat Treatment of Rail Foot**

The effect of the heat treatment is a softening of the rail base as well as of the base of the weld. Therefore, the capacity for plastic deformation during the bend test will improve.

In Table 2 a listing of slow bend test results is given. The deflection of welds that had been exposed the post heat treatment lay between 14 mm and nearly 27 mm. Thus it becomes obvious that the deflection can really be increased.

Based on experience a few welds were additionally thermally isolated with mineral wool for about 15 minutes after the heat treatment. The decelerated cooling has an additional (but small) positive effect with regard to the deflection values. In the given case values between 16 mm and about 25 mm were found.

Table 2 Results of Slow Bend Tests and Hardness Measurements

test configuration			Brinell hardness HBW 5/750 (running surface)	break load [kN]	deflection [mm]
welding procedure	post heat treatment	decelerated cooling			
SkV	–	–	351	1548	9,70
SkV	–	–	341	1650	10,60
SkV	✓	–	354	1792	14,40
SkV	✓	–	365	1619	14,70
SkV	✓	–	353	1813	15,70
SkV	✓	–	342	1805	16,06
SkV	✓	–	373	1930	20,80
SkV	✓	–	352	2028	26,60
SkV	✓	–	362	2066	26,90
SkV	✓	✓	347	1776	16,00
SkV	✓	✓	350	1797	17,00
SkV	✓	✓	343	1872	19,00
SkV	✓	✓	382	1868	22,70
SkV	✓	✓	345	1795	23,00
SkV	✓	✓	384	1971	24,60

Based on the given results can be summarized that it is possible to improve the static bend properties of welds (in this example full-hardened R65 rails) by means of an additional heat treatment of the weld base.

In this example it was not possible to reach the aim of a deflection of 20 mm minimum for every test weld during the slow bend test, but it was possible to prove that 20 mm could be achieved in about 50% of the tests. Compared to the untreated welds an improvement of at least 50% was observed.

This result is quite remarkable, because the measured break loads as well as the corresponding deflections can generally be considered as very good for head-hardened or full-hardened rails. Moreover, it should be questioned if the demand for 20 mm as minimum required value is really appropriate with regard to aluminothermic weld joints of high strength rails.

5. Conclusions

In this report it could be shown that post treatments are available to improve static and fatigue properties of aluminothermic welds.

On the one hand it was shown that an impact treatment of the transition from rail to weld collar can clearly improve the fatigue properties of the aluminothermic welds. On the other hand could be shown that a selective heat treatment of the weld base can lead to a noticeable increase of the deflection during the slow bend test.

With this two examples of mechanical and thermal treatments are given that could be applied successfully to enhance the weld properties. Technical modifications of the described methods are possible – it is not the aim of this report to give a list of all (theoretically) possible post treatments. The chosen examples are methods that are already used in praxis.

In principle, both techniques are very easy to be handled on a laboratory scale. The treatment of the welds comprises no risks as long as the techniques are executed correctly.

But for both techniques should be considered carefully if they are economically applicable. Both techniques can be used during installation or repair of the track. At least the heat treatment method is used in Russia for aluminothermic welding of R65 rails. Nevertheless, the usage of both techniques requires additional effort and time. This additional effort must always be kept in mind if a technique is introduced into the market.

On a technical basis both techniques have a positive effect on the performance of the weld and should be applied in those cases where the usage is really required and meaningful. E.g. the “typical” aluminothermic weld that is commonly used does not fail due to fatigue cracks. Only for heavy haul tracks fatigue is a serious problem – the ultrasonic impact treatment could be used here successfully. Therefore, the fields of applications of the different post treatments should be taken into account.