Journal of Mechatronics, Automation and Identification Technology

Vol. 1, No.1. pp. 15 – 20

Influence of welded Joint Structure on Fatigue Strength of the Impact Loaded Weld Fillet Joint between Radial Carrier and Rapping Device Drive Shaft

Josip SERTIĆ[1], Dražan KOZAK[2], Damir ŠIMUNIĆ[1], Ivan SAMARDŽIĆ[2], Ivan GELO[2], Dino BUČEVIĆ-KERAN[3]

[1] Đuro Đaković Termoenergetska postrojenja d.o.o., Dr. Mile Budaka 1, HR-35000 Slavonski Brod
[2] Mechanical Egineering Faculty, Trg Ivane Brlić-Mažuranić 2, HR-35000 Slavonski Brod
[3] Đuro Đaković Holding d.d., Dr. Mile Budaka 1, HR-35000 Slavonski Brod
josip.sertic@ddtep.power-m.hr, drazan.kozak@sfsb.hr, damir.simunic@ddtep.power-m.hr, ivan.samardzic@sfsb.hr, ivan.gelo@sfsb.hr, dino.bucevic@ddsv.hr

***Abstract*— Cleaning heat exchanger surfaces of the steam boiler from layers of ash ensures higher heat energy efficiency of the smoke. With harp type heat exchangers for cleaning it is possible to apply mechanical rapping devices which are used in a waste incinerator steam boiler in Riverside. That device is composed of rapping device drive shaft with welded radial carriers. The fracture of the welded joint between radial carrier and rapping device drive shaft occurred during active work of a waste incinerator steam boiler in Riverside. Welded joint between radial carrier and drive shaft was made as double fillet weld. This welded joint is loaded with impact load which causes material fatigue due to the repetitive behaviour. This paper presents results of welded joint laboratory research. Hardness measuring and metallographic testing established current states of welded joints on a rapping device drive shaft. Conducted research enabled evaluation of the results procured through mathematical model, which was established during earlier research. Procured results proved the appliance of fillet weld joint loaded with impact load to be a bad choice. It has been confirmed that earlier suggested analytical calculation model is applicable with designing of a rapping device.**

***Keywords*— impact loading, fatigue, mechanical rapping device, double fillet weld, weld joint strength, metallographic testing, weld joint hardness, micro cracks in welded joint**

I. INTRODUCTION

In waste incinerator steam boiler, with incineration comes conversion of fuel chemical energy into heat energy which through thermodynamic process is converted into mechanical energy of overheated steam. Fuel in waste incinerators is municipal waste. During the process of incineration in a waste incinerator steam boiler, smoke carries ash particles. Because of undesirable chemical composition, ash is gathering on surfaces of the heat exchangers and is very hard to clean. Ash that gathered on the heat exchangers is reducing efficiency of a boiler, so it needs to be cleaned. For that purpose there are different systems for cleaning heat exchangers. Mechanical rapping system is often used when cleaning harp heat exchangers. Rapping device hammer is indirectly through stickler rapping the bottom base of the chamber of harp heat exchangers and is giving it kinetic energy. Kinetic energy, given to a harp through rapping, needs to be strong enough to make harp start swinging. During the swing of a harp inertial forces are appearing on the layers which are bigger then adhesive forces between surfaces of the heat exchanger pipes and layers of soil [1]. This causes the separation of ash layers appearing on surfaces of pipe heat exchangers. Radial carrier, Figure 1, is double fillet welded to a drive shaft and it carries a rapping device hammer. Because of mechanical motion of a raping hammer, radial carrier and drive shaft welded joint (later just welded joint) is exposed to an impact fatigue loading. This is the reason why after impact loading critical number of cycles on the rapping devices of a Riverside boiler the fractures of this welded joints occurred. In paper [1] mechanical rapping devices double fillet weld has been analysed. Suggested mathematical model, which can serve in designing mechanical rapping devices, will here be evaluated with results of the laboratory researches. Base of the strength calculations of filler welds is a mean force which is occurring during impact of the rapping device in a welded joint [1], and it can be calculated with

$$N_2 = \frac{m \cdot l \cdot \omega \cdot (k+1)}{6 \cdot \Delta t}, \quad (1)$$

where m is a mass of rapping device lever, l is length of the lever, k restitution factor, Δt duration of impact and ω angle speed just before the impact. Angle speed just before the impact [1] can be calculated according to

$$\omega = \sqrt{\frac{2 \cdot g \cdot (m + 2 \cdot m_2)}{l \cdot \left(\frac{m}{3} + m_2\right)}}, \quad (2)$$

where m_2 is a mass of rapping device hammer, and g is gravitational acceleration.

Impact loading is very complex mechanical problem which in general case can include large deformations, material non-linearity, elastic and plastic stability and material properties during high speeds of deformations [2,3]. Impact physics contains energy sustainability law and the law of momentum. Energy dissipation in contact area of the impact is hard to predict, therefore a law of momentum is a base for mechanic impact study. During the rapping device impact on the bottom surface of harp chamber elastic deformation of the harp is occurring, as well as local plastic deformations in the area of impact. According to St. Venant's principal, effects of local deformation can be secluded from harp's global response during impact loading and they can be separately considered. Mathematical model in the paper [1] is derived for elastic deformation of the heat exchanger harp. Local plastic deformations are not considered.

In the paper [4] influence of impact loading on the heat exchanger harp's strength was researched. It suggested the analytical method for determining equivalent force of the rapping device. This analytical calculation method was applied in calculation of the heat exchanger harp's strength of the waste incineration facility in Vaasa [5].

Fracture occurred not only because of the undesirable geometries of the welded joint, but it is also assumed that it happened because of undesirable microstructure surface of the welded joint. Since material fatigue is a problem of surfaces, considerable enhancements of fatigue strength can be achieved with surface heat treatments [6]. Due to the frequent rapping device impacts, this welded joint is exposed to high frequency fatigue. High-frequency fatigue during impact loading on the construction steels was researched by B. S. Shul'ginov [7], and it was proved that with the same amplitude of dynamical loading value of the permanent dynamical strength of the tested material is somewhat larger for impact loading then for harmonic loading. Influence of the impact loading on the steel's fatigue strength under room temperature was researched and it can be found in [8-11].

Analytical strength calculation model of the welded joint between radial carrier and rapping device's drive shaft, which is presented in the paper [1], was developed for the project's needs of the waste incineration facility in Riverside [12], and it was a further development of the research done in [4,5].

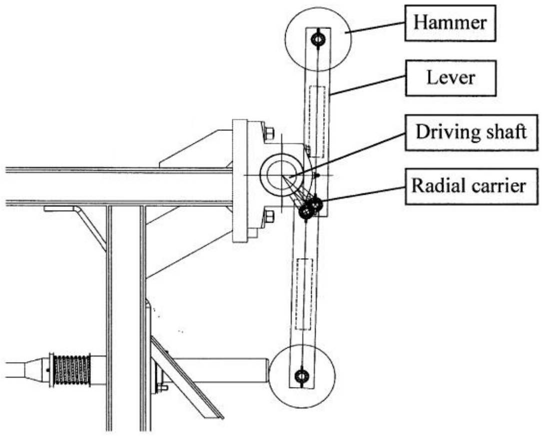


Fig. 1 A Basic construction elements of the mechanical raping device important for the analysis

II. Laboratory Research

Laboratory researches were conducted on rapping device's drive shaft with welded radial carriers, Figure 2. Welded joint fracture occurred at shorter radial carriers. In paper [1a] calculations were conducted for shorter radial carriers, which are here going to be tested visually, ultrasonically, by measuring hardness and by metallographic testing. For determining validity of chosen additive material in welding, chemical analysis of welded joint and base material of the shaft will be conducted. Drive shaft contains 14 radial carriers. After visual and ultrasonic testing two samples of the welded joints were selected, on which hardness and metallographic testing will be conducted, Figure 2. "Weld 6" was selected because of detected ultrasonic micro-crack, "Weld 10" was selected because of occurrence of the fracture and total separation of radial carrier from the drive shaft (Figure 3). In "Weld 10" adhesive connecting was detected, which reduces carrier capacity of the welded joint.

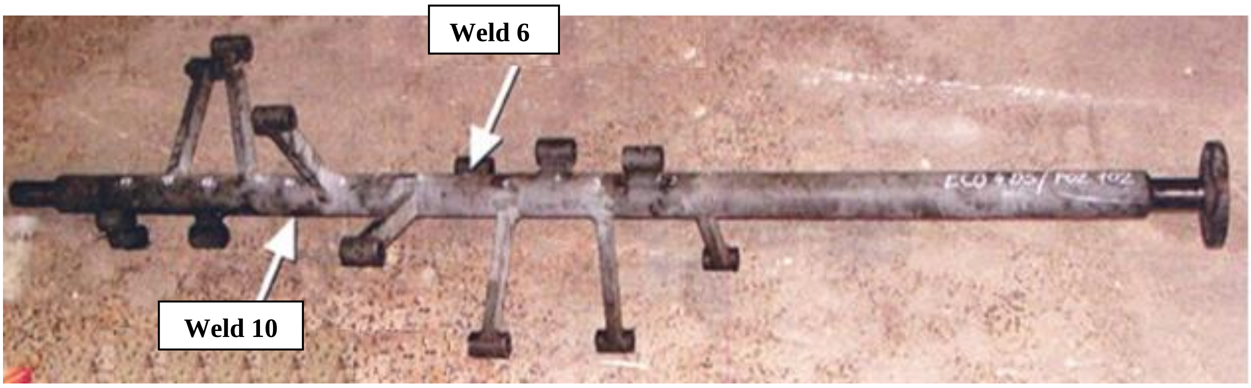


Fig. 2 Rapping device's drive shaft with welded radial carriers.

Fig. 3 Complete separation of the radial carrier from the drive shaft (“Weld 10”)

Samples “Weld 6” and “Weld 10” were cut from drive shaft. On “Weld 6” three cross-sectional surfaces were made, one on the beginning of the welded joint, one in the middle and one on the end (Figure 4). Sample “Weld 10” was cut only in the middle of the weld joint (Figure 5). Visual testing of the samples proved that welded joint was made in one passing of the tool. At welded joints were visible cavities of unacceptable dimensions, as well as adhesive connections, especially with welded joint of the radial carrier and the shaft.

Chemical analysis was conducted for basic material of the drive shaft and for the weld material in melting area. It was determined that basic material contains 0,21 % C, 0,21 % Si, 0,83 % Mn, 0,012 % P i 0,012 % S. In the melting area has been determined 0,18 % C, 0,48 % Si, 0,79 % Mn, 0,016 % P i 0,009 % S.

According to chemical composition it can be concluded that drive shaft was made from carbon steel and that appropriate additive material was used for the welding (electrode). From the results of hardness measuring it is possible to calculate tensile strength of the shaft material which is approximately 400 MPa.

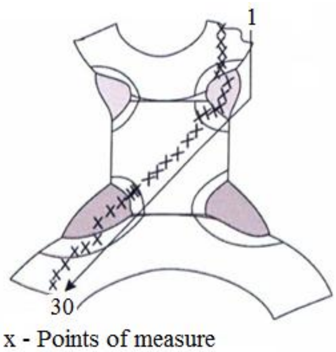
Weld beginning | Middle of weld | End of the weld

Fig. 4 Cross-sectional surfaces of the sample “Weld 6”

A. *Measuring Hardness*

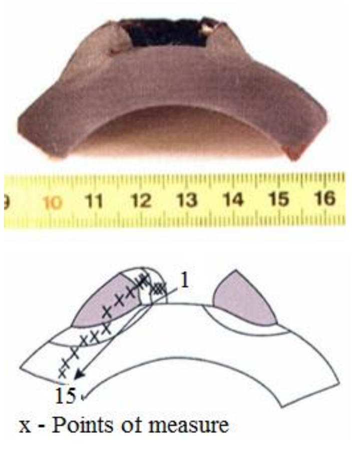
Measuring hardness was conducted on a sample “Weld 6” on the cross-sectional surface of the weld’s beginning (Figure 4). Measuring hardness was also conducted on the sample “Weld 10” on the cross sectional surface shown in Figure 5. Test results show that hardness is very high in the area of heat influences of the welded joint between drive shaft and radial carrier, even more then 300 HV10. That state of material in practical appliance is unacceptable. That caused the damage, i.e. adhesive disconnection, on the sample “Weld 10”. Measuring hardness was conducted according to the norm HRN EN 9015-1.

TABLE I RESULTS OF MEASURING HARDNESS FOR A SAMPLE “WELD 6”



X	Position of measure	Hardness HV10	X	Position of measure	Hardness HV10
1	PM	116	16	PM	121
2		127	17		125
3		139	18		130
4	HAZ	159	19	HAZ	169
5		170	20		171
6		179	21		175
7	W	210	22	W	240
8		209	23		230
9		207	24		232
10	HAZ	175	25	HAZ	349
11		167	26		353
12		160	27		351
13	PM	127	28	PM	175
14		124	29		171
15		122	30		160

TABLE II RESULTS OF MEASURING HARDNESS FOR A SAMPLE “WELD 10”



X	Position of measure	Hardness HV10
1	PM	152
2		147
3		151
4	HAZ	157
5		164
6		167
7	W	230
8		231
9		231
10	HAZ	337
11		324
12		317
13	PM	183
14		176
15		172

B. *Metallographic Testing*

On the same samples on which hardness measuring was conducted, metallographic testing was also conducted. Metallographic testing showed that basic material of the drive shaft and radial carriers has acceptable ferit-perlit structure. Highly expressed structural changes (tempered martensite) are visible in the area of heat influences, which confirms values of measured hardness (Picture 360). The presence of cross-sectional cracks during stresses was noticed with detailed analysis (Picture 357). On the sample “Weld 10” additionally were also noticed errors caused by welding procedure which led to, because of stress, occurrence of cracks which caused the fracture (Picture 345, 345a and 345b). Figures 6 and 7 show measured places used for metallographic testing of samples “Weld 10” and “Weld 6”.

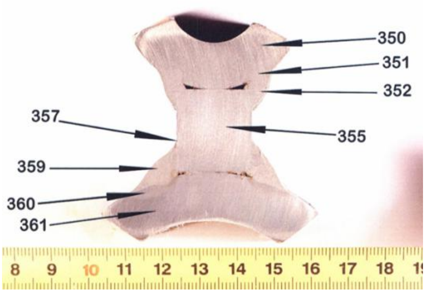


Fig. 6 Measured places for “Weld 6”

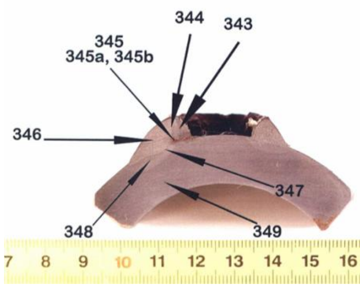
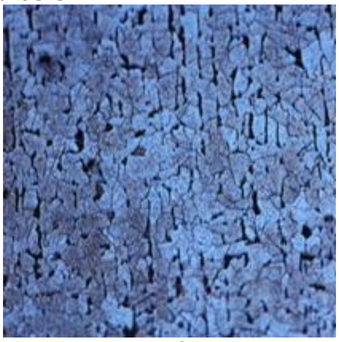


Fig. 7 Measured places for “Weld 10”

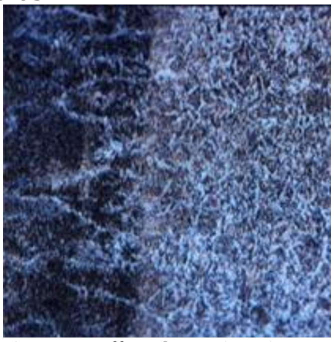
Picture 343



Location: Parent material (PM)

Description: Fine-grained ferrite pearlite structure

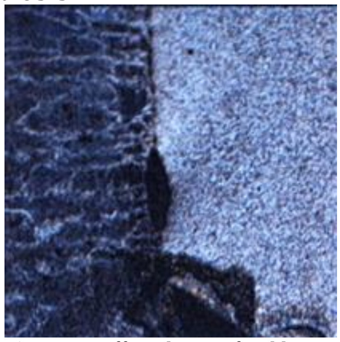
Picture 344



Location: Heat affected zone (HAZ)

Description: Fine-grained, recrystallized structure of materials

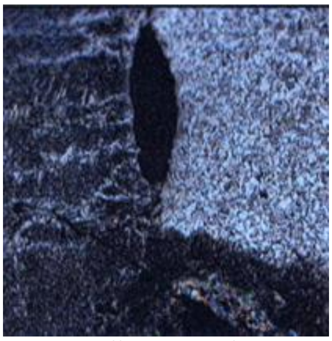
Picture 345



Location: Heat affected zone of welds - vertical carrier (HAZ)

Description: Defects in the form of cracks and cavities revealed in the joint of the weld and vertical carrier

Picture 345a



Location: Heat affected zone of welds - vertical carrier (HAZ)

Description: Detail

Picture 345b

Location: Heat affected zone of welds - vertical carrier (HAZ)

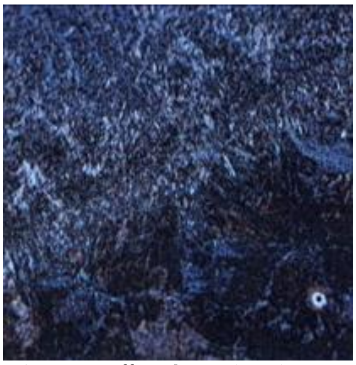
Description: Longitudinal crack which is moving from the perceived voids.

Picture 346

Location: Weld (W)

Description: Dendrite material structure

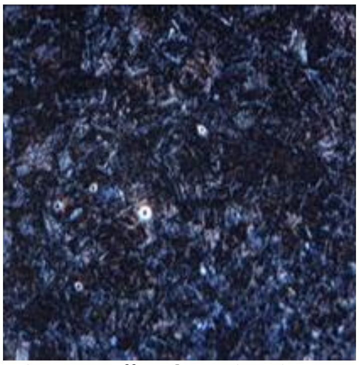
Picture 347



Location: Heat affected zone (HAZ)

Description: Recrystallized material structure

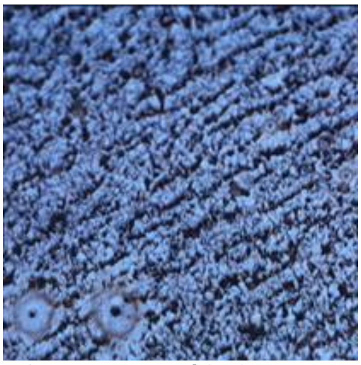
Picture 348



Location: Heat affected zone (HAZ)

Description: Tempered material structure

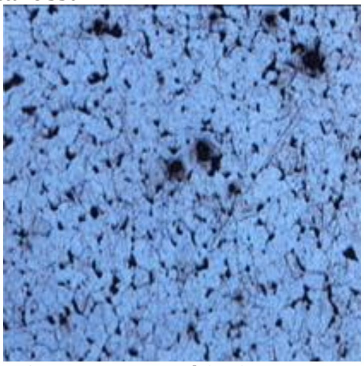
Picture 349



Location: Parent material (PM)

Description: Oriented ferrite-pearlite structure

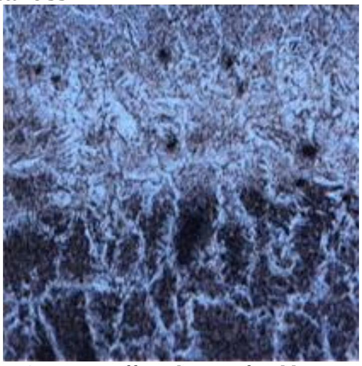
Picture 350



Location: Parent material (PM)

Description: Fine-grained ferrite pearlite structure of the material

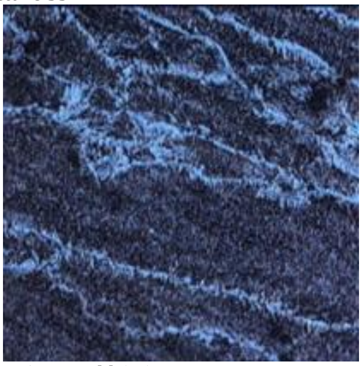
Picture 351



Location: Heat affected zone of welds - vertical carrier (HAZ)

Description: Recrystallized material structure

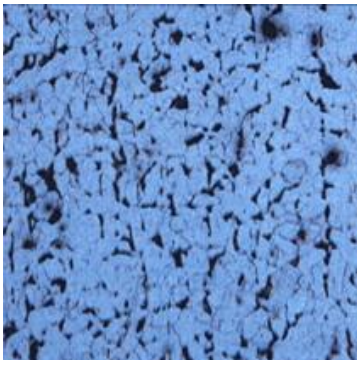
Picture 352



Location: Weld (W)

Description: Dendrite material structure

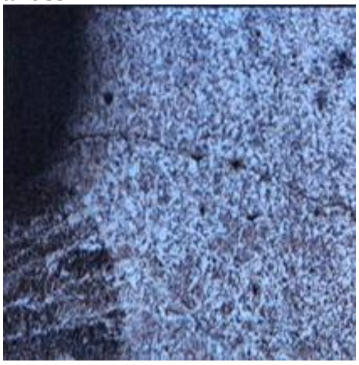
Picture 355



Location: Parent material (PM)

Description: Ferrite-pearlite structure of the material

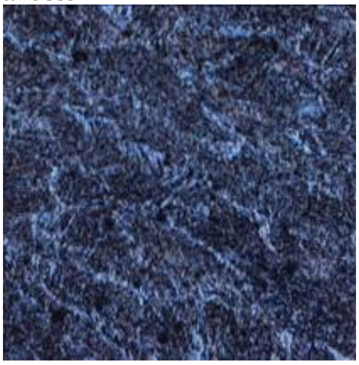
Picture 357



Location: Heat affected zone (HAZ)

Description: In the material formed transversal cracks can be observed

Picture 359



Location: Weld (W)

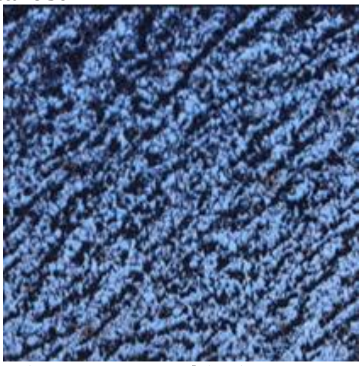
Description: Dendrite material structure

Picture 360

Location: Heat affected zone (HAZ)

Description: Recrystallized material structure

Picture 361



Location: Parent material (PM)

Description: Fine-grained ferrite pearlite structure of the material

III. Conclusion

For determining condition and structure of the welded joint material, hardness measurement and metallographic testing were conducted. Conducted research determined that technological forming of the joint between radial carrier and drive shaft was not very well chosen because of choosing fillet weld instead of double bevel T-joint. That formed cavities between radial carrier and drive shaft, which because of the notch influences, represent initial places for appearance of new occurring damages and fractures. That has, especially in this case, a big significance because the welded joint of radial carrier and drive shaft was exposed to the impact fatigue loading. During the production compounds were made, in which occurred adhesive connecting, without the need of penetration. Since the size of the most radial carriers is significantly smaller then drive shaft, during the welding fast heat dissipation occurred, and its intensity influenced the structure degradation of annealing. With larger radial carriers this did not occur because it cooled slower. Results of the research show that, in the area of heat influence of welded joint the hardness is very high between drive shaft and radial carrier, even more then 300 HV10. That state of the material in practical appliance is considered unacceptable. That initiated, on sample “Weld 10”, appearance of damage. Highly expressed structural changes (tempered martensite) are visible in the area of heat influences, which confirms values of measured hardness. The presence of cross-sectional cracks during stresses was detected with detailed analysis (Picture 357). On the sample “Weld 10” errors caused by welding procedure were also noticed from which, because of stress, occurred cracks which caused the fracture.

If results of analytical calculations in paper [1] are compared with the laboratory researches, differences between defining carried capacities of welded joint of radial carrier and drive shaft can be recognized. Analytic calculations produced results that, with specific probability, can state that welded joint was properly dimensioned. Notch influences and mistakes with welded joint were not taken into consideration. Considering that the factor of restitution has the highest possible value (k = 0,8), and that the duration of impact occurred in the shortest time possible (Δt=0,0001s), then it is visible that the appearance of the crack in the welded joint has to come right after the first rapping device’s impact. With the necessary factor of safety (proposal S = 1,5), maximal value of restitution factor and minimal duration of impact, proposed analytical calculation model represents good base for dimensioning the welded joint between radial carrier and rapping device’s drive shaft. It is necessary to use double fillet weld with full weld (K-preparation of welded joint).

This paper shows that the use of fillet welds on impact and fatigue loaded constructions is dangerous. It was determined that undesirable martensite structures in the heat influence areas in combination with geometrical mistakes and undesirable impact and fatigue loadings can contribute to the appearance of welded joint fractures.

Proposed mathematical calculation model in paper [1] can give more accurate results if the value of impact duration was correctly measured and correct value of restitution factor is determined. In case that approved reasons demand welded joint to be a double fillet weld, for dimensioning of that kind of welded joint it would be necessary to apply fracture mechanics.

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