

## ENERGETIC ANALYSIS OF HARD FACING AND WELD CLADDING OF AN AIR POWERED DROP HAMMER DAMAGED RAM

by

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*This paper studies problems of hard facing of damaged and initially cracked mechanical engineering heavy parts of complex geometry such as large rams of air powered drop hammers. During long-term exploitation, these parts are subjected to thermal fatigue due to cyclic temperature changes and variable impact compression. Taking into consideration high ram costs and difficulties to purchase ram, the necessity of its reparation becomes obvious. The choices of the most suitable technologies of hard facing and welding of an initially cracked ram are also studied here. Besides the techno-economic analysis, an energetic analysis is performed as an additional criterion in assessment of the proposed technology.*

Key words: *reparation, hard facing, ram, energetic analysis*

### Introduction

Comprehensive theoretical, model and experimental investigations, as well as a detailed energetic and economic analysis, were performed in this paper with the aim to find a unique hard facing methodology for different technical systems parts, improve the existing technologies, choose right filler materials, reduce operating device delays, reach better economic and energetic effects during maintenance, avoid undesired hard facing effects and to perceive possibilities of hard facing and welding applications. Successful maintenance of different parts of forging devices is possible only if a general procedure of hard facing is established. The results obtained here show that positive effects can be expected only if this condition is fulfilled.

Masses of the studied rams vary from 2000 to 6000 kg, depending on the energetic capacity of the air powered drop hammers. This paper investigates the possibility of

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reparation of the biggest rams of the mass of about  $m_{UK} = 6000$  kg, including hard facing of initially cracked and damaged operating surfaces of the rams.

Note that, following the proposed technology, two rams have been successfully repaired so far. One of them has been used since 2002 and the other since 2005, which is significantly longer than the warranty period given by the manufacturers.

### Working environment for a ram of air powered drop hammer

The ram (figure 1) is exposed to impact compressive loads, and partially also to the temperature gradient, *i. e.* to the thermal stresses, caused by an unbalanced temperature field [1-6]. This intensively loaded mechanical part operates under very complex conditions since, during exploitation, it is exposed to mechanical and thermal loads of high intensity. After a long period of operation, *i. e.* after a high number of repeated cycles, cracks are observed on the ram, as shown in figure 1.

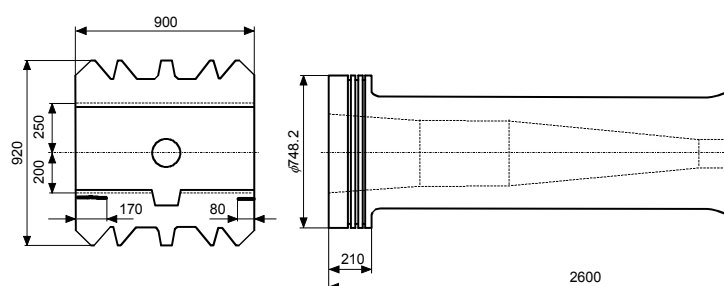


Figure 1. Appearance of the ram and places of the noticed cracks

The technology of manufacturing and reparation requires special efforts due to its large dimensions and complex shape, the fact that it is exposed to dynamic and thermal loads, and that is sized based on increased safety factors. One should also keep in mind the need for reliable exploitation of the repaired components, which can be best achieved by applying the appropriate structural integrity analysis, [7-12].

The ram of a air powered drop hammer, as one of the most highly loaded part in machinery, is made by forging from the low alloyed steel for tempering Č4731-JUS C.B9.021 (34CrMo4-EN 10083/1), (tab. 1).

Table 1. Chemical composition and mechanical properties of the ram

Position	Chemical composition, %							Mechanical properties				Hardness HB	Microstructure
	C	Mn	Si	Cr	Mo	P	S	$R_m$ , [MPa]	$R_{eH}$ , [MPa]	A, [%]	Z, [%]		
Hammer's ram	0.30-0.37	0.60-0.90	0.40	0.90-1.20	0.15-0.30	0.035	0.03	700-1000	270-380	15	60	≈ 300	Interphase structure

Note: Hammer's ram was also produced in Poland (Huta Zygmunt).

According to computation criteria for weldability estimation, this part belongs to the group of conditionally weldable materials, which should be preheated in order to prevent formation of brittle phases, *i. e.* cold cracks, because material is prone to hardening. The preheating temperature can be calculated or adopted based on empirical recommendations. In this case, the Seferian formula [13-15] is applied. It takes into account both chemical composition of the applied steel and the thickness of the welded part. The preheating temperature, somewhat over 300°C, is obtained, and taking into account the condition that it cannot surpass the temperature of martensitic transformation start, the temperature  $T_p = 300^\circ\text{C}$  is adopted [1, 2].

Investigations of the reparatory welding have shown that the local preheating has no significance in massive pieces due to the heat sink effect, which occurs during the process. Therefore, after the preparation of the cracked zones (grooves), massive pieces are preheated up to 350°C and are kept in the furnace for several hours (8 – 12 h). When a piece is removed from the furnace, it is covered by isolation cover in a way that only the zone, which is repaired by welding, is left uncovered. Since the reparation period is long, it is sometimes necessary to perform additional heating with the gas burner in order to sustain the preheating temperature. This additional heating has to be controlled, either by thermo-chalks or by corresponding digital devices. In this case, the preheating temperature was controlled by a digital instrument with thermocouple made of Cr-Ni-NiAl with measuring range from – 50 to 1200°C.

### Selection of the reparation procedure and the filler materials

It was decided to apply the procedure of manual metal arc (MMA) welding – hard facing. However, before performing the procedures on real parts, the corresponding welding tests were performed on models, in order to establish the optimum technology of hard facing.

The coated electrodes used for reparatory hard facing of the ram were manufactured by distinguished producer according to DIN 8575/84 with electrode E CrMo1B26 (tab. 2). Those thick shielded metal basic electrodes with controlled content of diffusive hydrogen were dried according to regime 350°C/2h, in order to obtain welds of good mechanical properties.

**Table 2. Filler metal properties**

Electrode sign mark	Chemical composition of the pure hard-faced layer, [%]						Mechanical properties			
	C	Mn	Si	Mo	Ni	Cr	$R_m$ , [MPa]	$R_{eH}$ , [MPa]	$A_5$ , %	$KV$ , [J] T= 20 [°C]
Standard DIN 8575/84										
E CrMo1B26	0.08	0.85	0.5	0.5	–	1.20	560-660	460-560	22-26	100-140

Hard facing of slider guides was performed with a coated electrode E CrMo1B26 [15], which usually serves for hard facing of worn surfaces with 280 – 330 HB of hardness, because of easy mechanical machining.

## Experimental model testing

### *Metallographic tests*

In order to select the best repairation technology the numerous tests were performed on models. Several models were hard faced in one or several passes (layers) either with preheating ( $T_p = 300^\circ\text{C}$ ) or without preheating (figures 2a, 2b, and 2c). Metallographic samples (blocks) were cut from such hard faced samples-models, as shown in figure 2-D. The hardness was usually measured in several directions, and the microstructure of the characteristic welded zones was estimated. Samples for hard facing were usually chosen according to the geometric similarity with the hard faced part and made of a material with the same chemical structure as the hard faced ram.

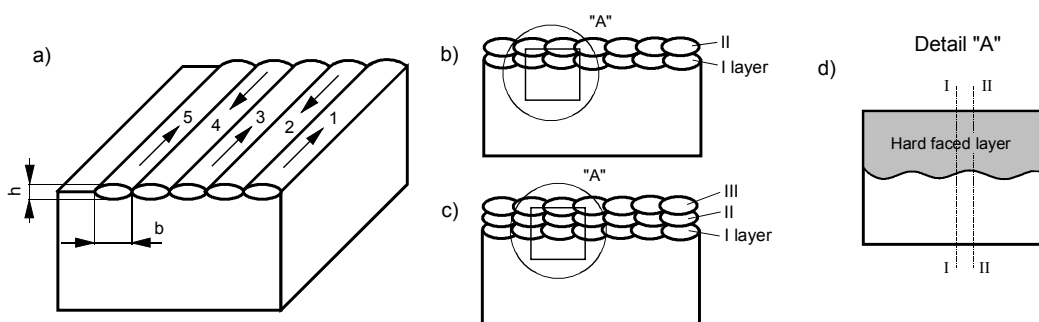
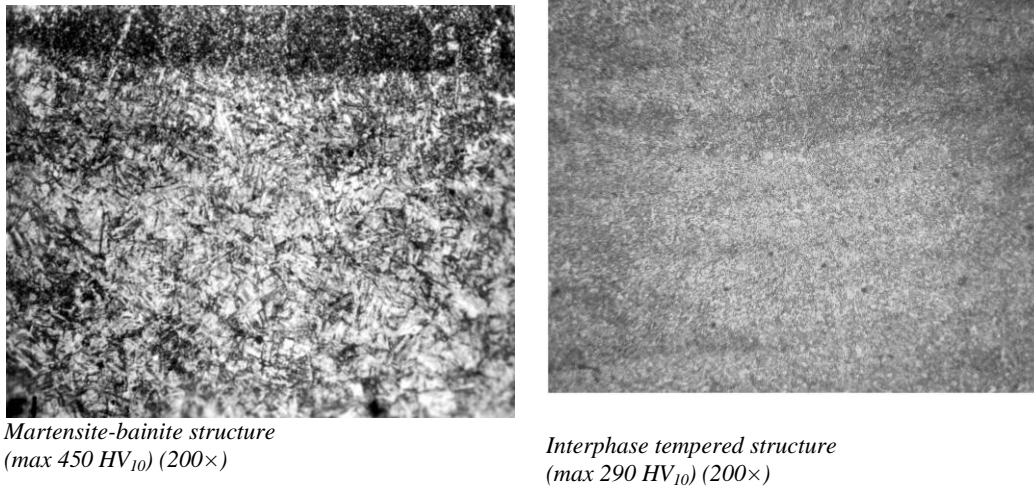


Figure 2. The order of the hard-faced layers deposition [1, 2]

After hard facing, the model samples (4 of them) were slowly cooled in the furnace. Two samples were tempered at  $650^\circ\text{C}/2\text{h}$ . They were first slow-heated in the furnace and then slow-cooled, while the two other samples were not thermally treated. The samples that were preheated and then tempered by E CrMo1B26 electrodes had the hardness under 350 HV. This suggests that there is no danger of brittle martensite phase formation in the hard faced zones if the prescribed technology is followed. In some characteristic zones of these samples, the following microstructures are observed: hard faced layer inter-phase carbide, HAZ inter-phase sorbite, and base material (BM) mainly sorbite. In the samples that are only preheated and not tempered, hardness over 350 HV was obtained, and the appearance of brittle phases – martensite and lower bainite was detected [1-3]. Figure 3 shows HAZ microstructures both for only preheated and preheated and then tempered sample– models.

The ram model was repaired with electrodes  $\phi$  3.25, 4.0 and 5.0 mm. The order of the hard faced layers deposition is presented in figures 2a and 2b. In this way, the optimum repairation technology suitable for the real part was determined (tab. 3). The microstructure analysis, hardness measurements, and visual examination confirmed that the weld layers did not have pores, cracks, ruptures and other failures and that the bond between the base material (BM) and the filler material was of good quality.



**Figure 3. Hard faced HAZ with and without tempered microstructure ( $T_p = 300^\circ\text{C}$ )**

**Table 3. Hard facing repairation parameters for the MMA procedure (E CrMo1B26)**

Repaired position	Electrode diameter, $d_e$ , [mm]	Welding current, $I$ , [A]	Working voltage, $U$ , [V]	Welding speed, $v_z$ , [ $\text{cms}^{-1}$ ]	Input heat, $q_i = \frac{U \cdot I}{v_s} \cdot \eta$ , [ $\text{Jcm}^{-1}$ ]
Ram model	3.25	75	23	0.085	13000
	4	170	27	0.160	22950
	5	200	28	0.169	26508

During the welding process, energetic parameters ( $I$ ,  $U$  and  $v_z$ ) were controlled, *i. e.* the input heat in the multi pass welds was in the range of  $Q_1 = 13000\text{-}26500 \text{ J/cm}$ . This energy enabled the necessary depth of the welded zone, suitable hardness and microstructure, and appropriate mechanical properties.

### Estimation of weldability on the basis of transformation continuous-cooling diagrams

Producer's catalogues and other references give corresponding transformational IRA and ARA diagrams which demonstrate changes of the cooled austenite and the influence of the temperature and time on the course of changes for steel Č4731 (34CrMo4). Despite the fact that these plots were made for steel of a particular chemical structure and for austenitization conditions, they can still be useful for estimation of some of the weld zones properties.

The KH diagram shows characteristic temperatures as well as periods of particular phase changes (figure 4). These readings depend on austenitization temperature, period of

heating, periods of holding constant temperature, grain size, austenite homogeneity, cooling conditions, sample size, *etc.*

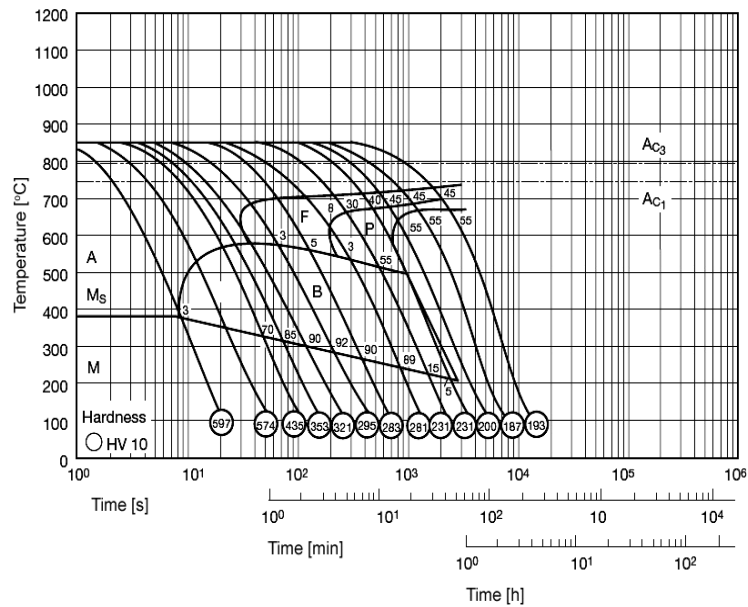


Figure 4. Continuous-cooling diagram for steel Č4731 (34CrMo4)

In order to ensure that the accepted procedure and weld regime lead to appropriate structure and mechanical properties (optimal toughness, hardness, and microstructure), besides the already described experimental methods, diagrams of continual cooling in welding conditions were used. The characteristic cooling time between 800 and 500°C ( $t_{8/5}$ ) was calculated based on the empiric formulas [4, 15-17] (tab. 4). When the characteristic time was put into the continuous-cooling KH (ARA) diagram (figure 4), it enabled the estimation of the HAZ structure and hardness.

Table 4. Values of the cooling time  $t_{8/5}$  ( $s = 30$  mm)

Electrode diameter $d_e$ , [mm]	Hard facing energy $Q_b$ , [Jcm <sup>-1</sup> ]	Preheating temperature $T_o = T_p$ , [°C]	Cooling time	Hardness	Microstructure
			$(t_{8/5})^J$ , [s]	$HV_{10}$	HAZ
3.25	13000	20	3.40	> 597	M
3.25	13000	300	12.6	≈ 574	M (predominantly)+B
4.00	22950	20	7.90	≈ 574	M
4.00	22950	300	29.6	≈ 353	M+B (predominantly)
5.00	26508	20	9.80	574 < HV < 597	M+B
5.00	26508	300	36.8	321 < HV < 353	M+B (predominantly)

The cooling time  $t_{8/5}$  was calculated according to Ito and Bessyo [13] because it was in accordance with the experimental data given in [4, 16, 17]. Thus, the concordance of experimental and theoretical results was confirmed [4, 16, 17].

Putting the calculated cooling time  $t_{8/5}$  into the KH-diagram for the given steel enables estimation of the novel structure and hardness of the HAZ. Based on the known cooling diagrams of some characteristic temperature cycle structures, the structures from the KH diagram and the results of metallographic measurements were compared (figure 3). The presented KH diagram (figure 4) shows that the limit cooling time has the value of  $t_{8/5} = t_{100} = 8.5$  s, which means that hard facing or welding performed with the input heat as shown in tab. 4 without preheating ( $T_o = T_p = 20^\circ\text{C}$ ) leads to a pure or predominantly martensite HAZ structure. Hard facing or welding performed with the same input heat but with preheating leads to a mixed structure (M+B) which is slightly less hard. Therefore, it is necessary to perform post tempering in order to lower the level of the residual stress and hardness of the HAZ as well as to increase the plasticity of certain hard faced zones.

Based on experimental results and references [4, 16-19], it has been confirmed that the computed cooling time, in a critical temperature interval, can be most accurately calculated using Japanese authors' formula [15]. In this way, the cooling rate can be determined accurately enough without expensive and time-consuming experimental procedures, which means that the aim of this investigation has been achieved. The cooling rate in the temperature interval of 800 to 500°C, determined with acceptable accuracy, enables readings of the structure and hardness from KH diagrams. Given the cooling rate and the corresponding transformation diagrams (TTT and KH) for the studied steel, it is possible to define the most suitable hard facing technology.

### **Hard facing of the considered part**

Before applying the optimum technology of hard facing, verified on models, a detailed control of observed damages was performed by visual inspection of the corresponding zones, magnetic defectoscopy, ultrasonic control and penetrating liquids. This enabled performing the adequate preparation of welding grooves (figures 5 and 6), bearing in mind that the groove root should reach the in-depth crack (see also figure 1).

Based on our previously conducted model investigations [1-4] and the results obtained by other authors [5, 6, 13, 20, 21], the decision to start this complex and risky reparation was reached. Difficult operating conditions, high impact and frequently repeated mechanical loads, elevated temperatures, *etc.*, made this process extremely complex. Furthermore, the reparation conditions were very unfavorable due to the position of grooves and cracks, complex cross sections and difficulties during the manipulation with these massive (about 6000 kg) and heated parts (about 300 °C).

For reparation of larger cracks, the construction of minimum volume grooves was planned (figures 3 and 4). Machining of grooves was first performed on two spindle milling copy machine and then it was finished manually [1-3].

When the grooves were prepared, the damaged part was placed into the horizontal furnace with an electro-resistance heater (figure 5), where it was first preheated and then heated through for several hours. After that, the ram was partially pulled out from the furnace chamber and the reparation process began.

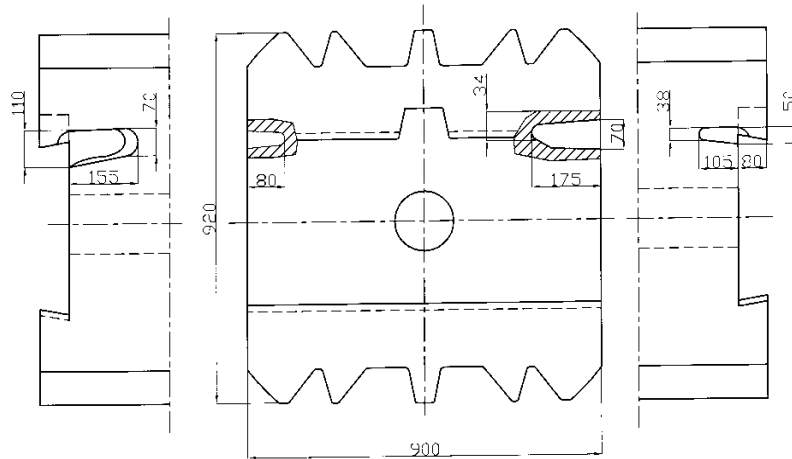


Figure 5. Shape and geometry of the prepared grooves

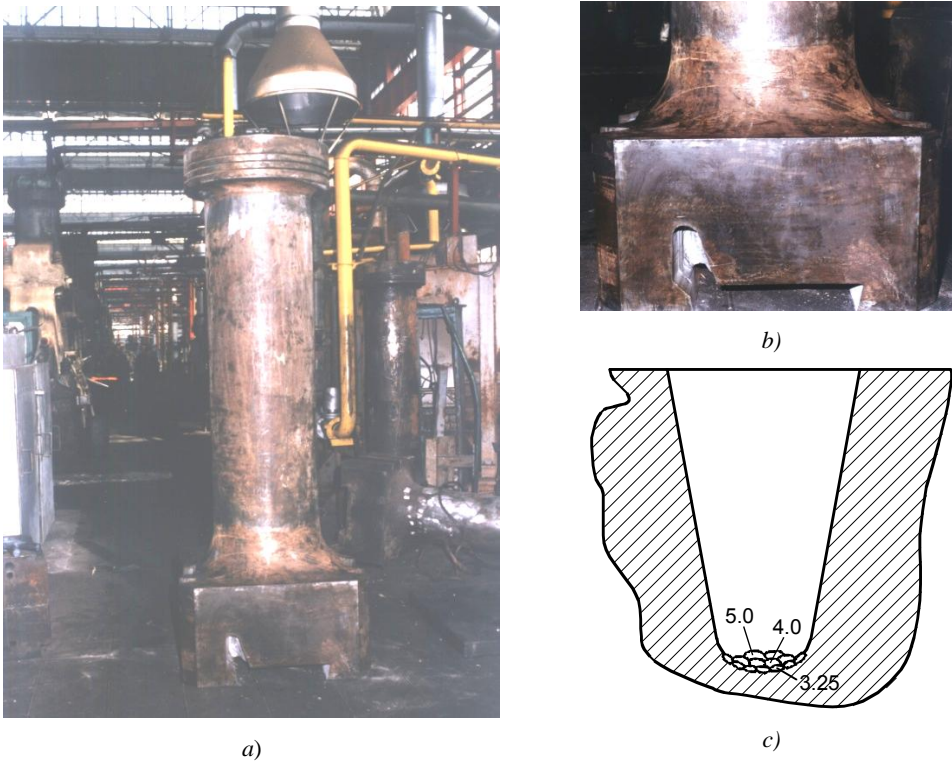


Figure 6. Appearance of the grooved ram (a, b) and weld pattern (c) [1-3]



Depending on the requirements, the part was either additionally heated with the gas heater and gas burner, or put back into the furnace, if the temperature of hard faced zones dropped down below 250 °C. The time needed for heating through of the ram, in the horizontal electro-resistance furnace (figure 7), was about 11 hours ( $T_p \approx 300$  °C). The reparation procedure was conducted according to scheme given in figure 6c. Root weld layers and fillers were welded first according to the prescribed sequence. The non-cooled welds, except for the root and cover layers, were forged by the tool with obtuse head. During the surface forging of the weld, one has to be careful that grooving does not cut over the depth. One must also take into account the strain hardening in order to preserve the impact toughness, therefore, the hot weld was forged only above the recrystallization temperature ( $T > 480$ °C). The total time for frame reparation was about four days (with two workers). The appearance of the repaired parts is given in figure 8.



**Figure 7. Preheating of the ram in the horizontal electroresistance furnace**



**Figure 8. Appearance of the ram after the hard facing**

### **Selection of an additional thermal and mechanical treatment**

Immediately after the welding operations, the ram was returned into the furnace and cooled down to the room temperature. Then, the thermal treatment was performed according to the regime  $T_t = 650$  °C/11 h (figure 9). After the tempering, it was necessary to perform a slow cooling of the ram in the furnace that was switched off [1-3]. Such a complex procedure of thermal treatment (prior, current and additional), was performed mainly because of the function of the ram, which imposes the necessity to minimize the unfavorable changes in the vicinity of the weld. This refers primarily to reduction of the residual stresses, decrease of hardness, obtaining of the unfavorable structure, easier diffusion of hydrogen, *etc.*

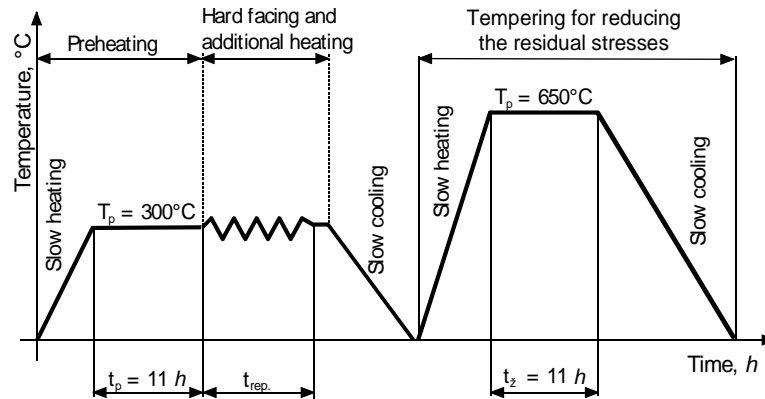


Figure 9. A complete cycle of the hard facing of the hammer's ram [1-3]

Figure 10 shows the dependence of the most important mechanical properties of the steel Č4731 (34CrMo4) in relation to the tempering temperature.

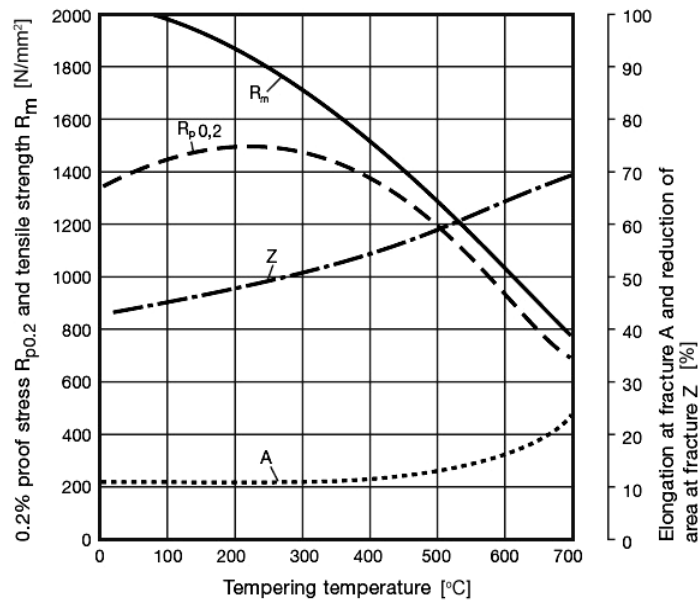


Figure 10. Steel properties at raised temperatures

After the thermal treatment, all weld grooves on the repaired ram were tested for compactness by ultrasonic defectoscopy and pneumatic fluids. The control was performed in an authorized laboratory for non-destructive testing. Neither external nor internal defects were found in the welded joints.

After an additional thermal treatment, ram of the air powered drop hammer was subjected to mechanical machining in order to obtain the original dimensions.

### Techno-economical analysis of the realized repairation

Hard facing technology is a complex set of different obligatory procedures in which many factors that may influence the cost of the work should be considered. In any of hard facing applications, the following factors should be considered: working conditions of the part that has to be repaired, damage identification, estimated weldability, weld technology, filler material, weld and hard facing regime, applied thermal treatment, final machining, model and actual parts examination, etc. Since the process is very complex, it is necessary to find the most suitable technical and technological solution and make the right decision whether to purchase a new part or to repair the old one [22, 23].

Techno-economical indicators of hard facing of ram of the air powered drop hammer are also considered in this paper. The following relevant data are taken into consideration.

### The cost of a new ram

According to the latest information, import of new part would cost about:  
 $C_{ND} = 83987.00$  €.

This price includes:

- Price of a new part  $C_{nd} = 67470.00$  €/ram,
- VAT (18%)  $C_p = 12144.00$  €/ ram,
- Customs duty (5%)  $C_c = 3373.00$  €/ ram,
- Transportation costs  $C_t = 1000.00$  €/ ram.

The structure of the above stated expenses is shown in figure 11.

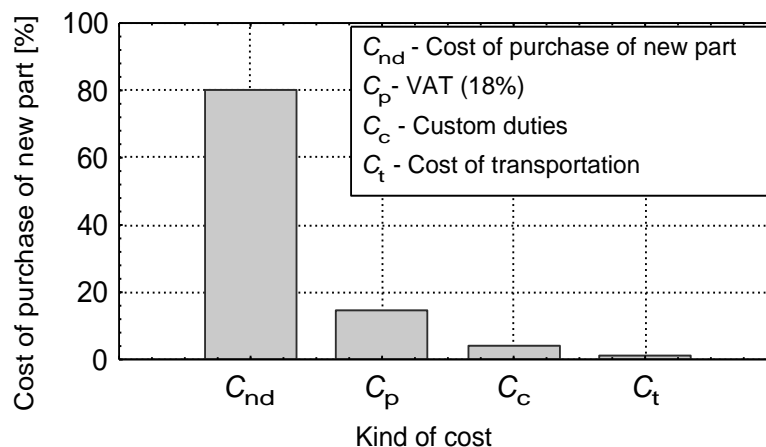


Figure 11. The structure of expenses for a new ram

### The cost of a repaired part

Repair expenses for the considered ram are  $C_R = 4912 \text{ €}$ , and they can be broken into the following parts:

- Damage identification  $C_{io} = 240.00 \text{ €/ram}$ ,
- Machining of damaged surfaces  $C_{mo} = 960.00 \text{ €/ram}$ ,
- Hard facing technology determination  $C_{otr} = 768.00 \text{ €/ram}$ ,
- Model verifying  $C_{mi} = 384.00 \text{ €/ram}$ ,
- Hard facing of the operating part  $C_{nrd} = 1600.00 \text{ €/ram}$ ,
- Cost of the hard faced surfaces machining  $C_{mo} = 960.00 \text{ €/ram}$ .

The structure of the above stated expenses is shown in figure 12.

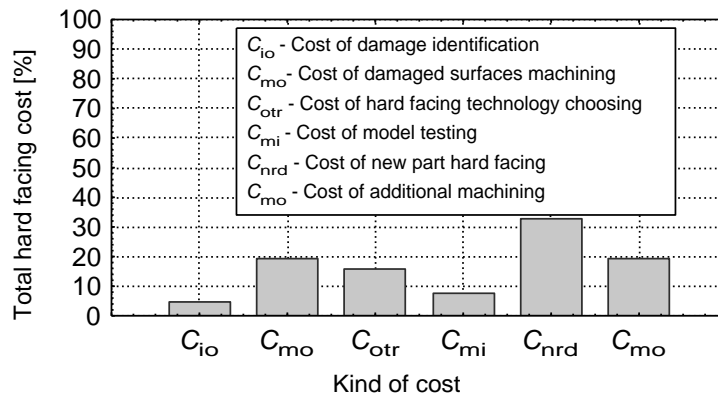


Figure 12. The structure of the greatest expenses for the ram repair

This leads to the conclusion that the total cost of hard facing is significantly lower (less than 6%) than the cost of purchase of a new part. Thus, the dilemma whether a new part should be purchased or the old one repaired by hard facing is solved even without taking into consideration the additional advantages those hard facing offers [1, 2, 22-24]. The hard faced bat considered here has been used in production since February 2002.

### Energy analysis

Hard facing of hammer's ram was performed using mainly electrical power and a small amount of inflammable gas. Depending on the hard facing phase, electrical power consumption can be separated into phases such as groove making, machining of worn sliding guides, preheating (figure 8), filling of the two pre-arranged grooves (figure 5), hard facing of worn sliding guides of tool core, additional tempering (figure 8), and additional machining.

All these ways of energy consumption will be further analyzed and explained.

### ***Consumption of energy in pre-machining – $Q_1$***

Ultrasonic defectoscopy registered two cracks (figure 1), and they were processed to make grooves that needed minimum deposit material (figures 5 and 6). Damaged bat sliding guides were also machined. Machining time of the two used axle milling machine with the power  $P_1 = 20$  kW was  $t_1 = 30$  h. Thus, energy consumption was  $Q_1 = P_1 t_1 = 600$  kWh.

### ***Consumption of energy during preheating – $Q_2$***

After machining, the ram underwent a slow heating in the horizontal chamber electrical heater for approximately 9 hours before the preheating temperature of  $T_p \approx 300$  °C was reached. That temperature level was kept for approximately 11 hours, with additional heating when the temperature dropped down below 250 °C, which was for about 20 hours. The power capacity of the heater was  $P_2 = 120$  kW, which lead to the consumed energy of  $Q_2 = P_2 \sum t_i = 4800$  kWh.

### ***Consumption of energy during hard facing – $Q_3$***

A detailed procedure for calculation of the consumed energy is given in [2], and in this case, it has the value of  $Q_3 \approx 48$  kWh.

### ***Consumption of energy during hard facing of sliding guides – $Q_4$***

A detailed procedure for calculation of the consumed energy is also given in [2], and in this case, it has the value of  $Q_4 \approx 20.5$  kWh.

### ***Consumption of energy during tempering process – $Q_5$***

After hard facing, the ram was put back in the electrical heater and it was slowly cooled until the room temperature was reached. Then it was slowly heated for approximately 19 hours until the preheating temperature,  $T_t \approx 650$  °C, was reached. This temperature was held for approximately 11 hours, and then, it was slowly cooled. The power capacity of the heater was  $P_2 = 120$  kW, with the consumed energy of  $Q_5 = P_2 \sum t_i = 3600$  kWh.

### ***Consumption of energy during additional machining process – $Q_6$***

After cooling of the hard faced ram, damaged sliding guides were machined on a two axle-milling machine. The machining time was  $t_6 = 20$  h, and the milling machine power was  $P_6 = 20$  kW. Thus, the energy consumption was  $Q_6 = P_6 t_6 = 400$  kWh.

### ***Total consumption of energy during reparation process – $Q_T$***

The total consumption of electrical energy  $Q_T$  during the reparation process of the hammer's ram was  $Q_T = \sum Q_i = 9468.5$  kWh. The energy consumption histogram is shown in figure 13.

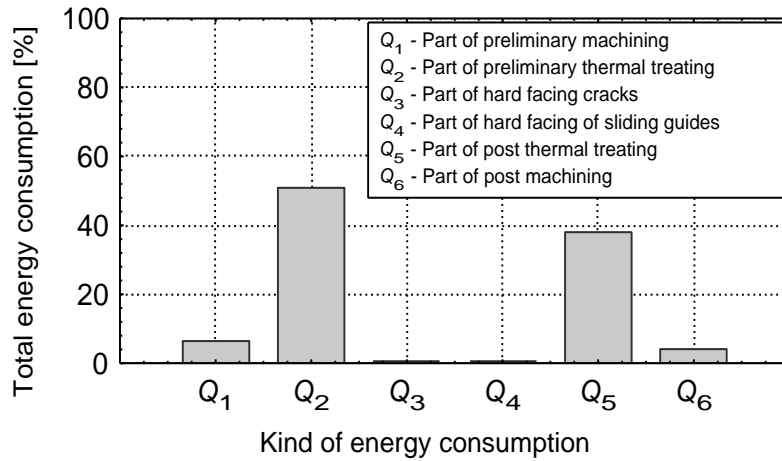


Figure 13. The structure of energy consumption for repair of the hammer's ram

Energy consumption given in bat unit mass is:

$$\frac{Q_{UK}}{m_{UK}} = \frac{\sum_{i=1}^6 Q_i}{m_{UK}} = \frac{9468.5 \text{ kWh}}{6000 \text{ kg}} = 1.5781 \frac{\text{kWh}}{\text{kg}}$$

### Total energy consumption for primary production of steel – Č4731

According to producer's data (tab. 5), the total energy consumption for production of one kilogram of tool steel for is 4.12 kWh of electric energy and 0.496 Nm<sup>3</sup> of burning gas.

Table 5. Total energy consumption for production of one kilogram of tool steel

Activity – process phase	Total energy consumption, [kWh kg <sup>-1</sup> ]	Burning gas consumption, [Nm <sup>3</sup> ]
1. Production of 1 kg of row iron	1.26	0.150
2. Production of 1 kg of tool steel	2.86	0.346
Total energy consumption	4.12	0.496

Therefore, based on the energy consumption analysis, it can be concluded that reparation of a damaged and worn hammer's ram is justified because the electric energy consumption for reparation of the ram is 2.6 times less than for production of a new one (figure 14).

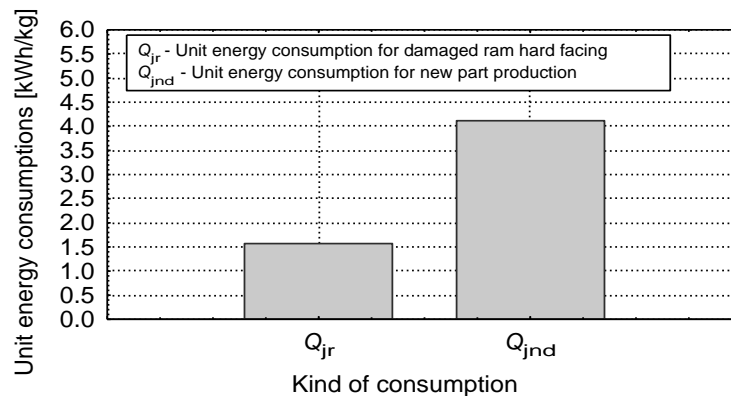


Figure 14. The structure of energy consumption for reparation of the hammer's ram ( $Q_{jr}$ ) and for purchase of a new one ( $Q_{jnb}$ )

### Concluding remarks

A complex examination of model and final testing of the hard faced ram have indicated that proposed technology of hard facing can give satisfactory results in real operating conditions. It was necessary to perform pre heating and additional thermal treatment, such as tempering, to lower level the residual stresses. A model metallographic examination and hardness measurements did not indicate quench structures in the proposed hard facing. Furthermore, the usage of based dry electrodes decreased a risk of cold cracks development, which made hard faced part reliable and safe for operation.

Application of these new advanced hard facing technologies leads to huge savings. They are obvious considering the fact that cost of hard facing is approximately 6% of the cost of a new ram production. The best way to promote a new technology is through measurable technical and economic results, which are here confirmed by successful hard facing of a part of a huge mass and complex geometry. The repaired ram described in this paper has been in a continuous operation since 2002. The life cycle of the repaired ram is well above the expected. Moreover, it has highly exceeded the producer's warranty period for a new ram.

A detailed analysis of energy consumption has proven hard facing to be justified. The energy consumption in hard facing was much less that in production of a new part. Finally, besides all technical, economic, and energetic advantages, hard facing has a positive effect on global environment protection.

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