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# SELECTION OF THE OPTIMAL HARD FACING (HF) TECHNOLOGY OF DAMAGED FORGING DIES BASED ON COOLING TIME $t_{8/5}$

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In exploitation, the forging dies are exposed to heating up to very high temperatures, variable loads: compressive, impact and shear. In this paper, the reparatory hard facing of the damaged forging dies is considered. The objective was to establish the optimal reparatory technology based on cooling time $t_{8/5}$. The verification of the adopted technology was done by investigation of the hard faced layers microstructure and measurements of hardness within the welded layers' characteristic zones. Cooling time was determined theoretically, numerically and experimentally.

*Key words:* Forging dies, hard facing, cooling time $t_{8/5}$, hardness, microstructure

## INTRODUCTION

The subject of this paper was problems related to hard facing of the damaged forging dies. These tools are exposed to extremely high temperatures, as well as to high compressive and shear loads, including impact loads. Steels that are used for manufacturing of such tools have to sustain high impact loads, to be resistant to wear and thermal fatigue, while maintaining the good mechanical properties at the same time, what was the main research topic in [1]. Similar problems were considered in paper [2], namely an analysis of stresses and failure causes during exploitation was done at cemented carbide punch used for the manufacturing of the airbag container type parts. Thermal fatigue was also cause of failure of a tool for pressure casting analyzed in [3]. Analysis of crack appearance after certain number of cycles was done for the aluminum casting process. In paper [4] is given the procedure for analysis of failure causes of a device for soil Tamping Tool, where the failure occurs due to very harsh mechanical and tribological working conditions. Forging dies are subjected to all of the mentioned damages, and for them in [5], based on model investigations, the hard facing technology was prescribed [5]. For production of forging tools alloyed steels are usually used, which do not possess very good weldability. Due to alloying, those steels are prone to self-hardening. In order to obtain good properties of the hard faced layer it is necessary to determine the temperature cycles beneath it, as well as the cooling time between 800 and 500 ºC, the so-called $t_{8/5}$. Influence of $t_{8/5}$ on mechanical properties of the hard faced layer is significant, while the methodology for its determination could be different. In papers [6,7] is presented a method for determination of the temperature cycle by the Smitweld simulator, on a certain number of samples, with variation of the maximal temperature and holding time. In paper [8] is shown the possibility of simulation of a temperature cycle by the thermo-mechanical device controlled by the Rikalin's mathematical model. Numerical analysis can be also reliably used for determination of temperature cycles, what was shown in paper [9] for the hard facing process and in paper [10] for the friction stir welding. Besides the optimal hard facing technology and selection of filler materials, it is also necessary to define the corresponding heat treatments. One has to determine the temperature cycles that appear during the hard facing, in order to avoid appearance of undesirable phases in the layers structure. The objective was to define the optimal hard facing technology for reparation of forging dies based on the cooling time $t_{8/5}$. To achieve that, the temperature cycles were investigated and the critical cooling time $t_{8/5}$ was determined theoretically, based on the Rikalin's formula, formula for the limit thin sheet's thickness and the Ito-Bessyo formula, [11], as well as numerically and experimentally. The criteria of the executed hard faced layers' quality were hardness and microstructure in layers of the applied hard faced welds and in the heat-affected zone (HAZ) under the weld.

## HARD FACING PROCEDURE

The forging dies usually operate at temperatures higher than 300 °C. Commonly used steels are 55NiCrMoV6 (for dies, pressing molds, dies holders), 56NiCrMoV7 (for dies and their inserts of extremely loaded pressing tools, press dies and extruders), X40CrMoV51 (for dies and their inserts for forging machines, casting

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molds, presses' thorns) and steel X32CrMoV33 (for dies, forging tools, screws manufacturing). In this paper, experiments were conducted on two steels: 56NiCrMoV7 and X38CrMoV51 (DIN 17350). The chemical composition and mechanical properties of those steels are given in Tables 1 and 2 [5].

Table 1 **Composition of used steels [5]**

| Alloying elements / % | 56NiCrMoV7 | X38CrMoV51 |
|---|---|---|
| C | 0,55 | 0,40 |
| Si | 0,3 | 1,0 |
| Mn | 0,7 | 0,4 |
| P | 0,035 | 0,025 |
| S | 0,035 | 0,025 |
| Cr | 1,1 | 5,0 |
| Ni | 1,7 | - |
| Mo | 0,5 | 1,3 |
| V | 0,12 | 0,4 |

Table 2 **Mechanical properties of used steels [5]**

| Steel properties | | 56NiCrMoV7 | X38CrMoV51 |
|---|---|---|---|
| Soft annealing | $T$ / °C | 670 - 700 | 800 - 830 |
| | $HV_{max}$ | 250 | 250 |
| | $R_m$ / MPa | 850 | 850 |
| Tempering | $T$ / °C | 400 - 700 | 550 - 700 |
| | $HV_{max}$ | 50 - 30 | 50 - 30 |
| | $R_m$ / MPa | 1 700 - 1 100 | 1 700 - 1 100 |

All the samples were treated in the same way as the original materials of real forging dies - quenching + tempering, so they could be as close as possible to real operating conditions. The hardness on selected samples (after heat treatment) was 40 - 42 HRC for 56NiCrMoV7 and 41 - 49 HRC for X38CrMoV51. The soft annealing was not performed, though the hardness was $HV > 350$, since mechanical processing was mainly done by grinding. Since hard facing was also done on samples of the thicker cross sections (s = 40 - 45 mm), it was necessary to preheat them since they are made of steels which are prone to self-hardening. The adopted preheating temperature was $T_p \approx 300$ °C, calculated according to Seferian's formula [5]. The proposed technological parameters of hard facing are shown in Table 3 [5]. That implied that the layers should be deposited in several passes (2 or 3). The cause for this is the necessity to reduce the degree of dilution, i.e., to obtain the declared weld properties prescribed by the electrodes manufacturers. The preheating temperature, i.e. the interpass temperature was always checked before the next layer was to be deposited. Measuring device was Tastotherm D120 (with NiCr-NiAl thermocouple and measurements range of - 50 to 1 200 °C).

As the filler metals the two high-alloyed rutile electrodes (Table 4): UTOP 38 and UTOP 55 were used. Those filler metals are intended for hard facing of tools, for cold and hot forming of steels and other metals, like steel molds, dies and pressing thorns. Hard faced layers, executed by those electrodes, should possess high toughness and wear resistance. Their hardness is stable up to temperature of 600 °C. Prior to hard facing electrodes were dried in the furnace up to 350 – 400 °C, maintaining for 2 h at the drying temperature and cooling in the furnace for 1 h, when the temperature did not fall below 150 °C.

Table 3 **Hard facing parameters for the Manual Metal Arc Welding procedure [5]**

| MMAW properties | Electrode mark | |
|---|---|---|
| | Steel plant "Jesenice"/DIN 8555 | |
| | UTOP 38/ E3-UM-40T | UTOP 55/ E6-UM-60T |
| Core diameter / mm | 3,25 | 5,00 |
| Welding current / A | 115 | 190 |
| Voltage / V | 26 | 29 |
| Welding speed / mm/s | ≈ 2,8 | ≈ 2,5 |
| Driving energy / J/mm | 854,3 | 1 763,2 |

Table 4 **Filler metal properties [5, 12]**

| Filler metal properties | | Electrode | |
|---|---|---|---|
| | | Steel plant "Jesenice"/DIN 8555 | |
| | | UTOP 38/ E3-UM-40T | UTOP 55/ E6-UM-60T |
| Chemical composition / % | C | 0,13 | 0,50 |
| | Cr | 5,0 | 5,0 |
| | Mo | 4,0 | 5,0 |
| | V | 0,20 | 0,60 |
| | W | in traces | in traces |
| Current type | | = (+) | = (+) |
| Hardness/ HRC | | 36 - 42 | 55 - 60 |

Electrodes were used for hard facing of the preheated samples, what resulted in decrease of the hydrogen diffusion and elimination of cold cracks appearance. The hard faced layer deposition sequence is shown in Figure 1a.

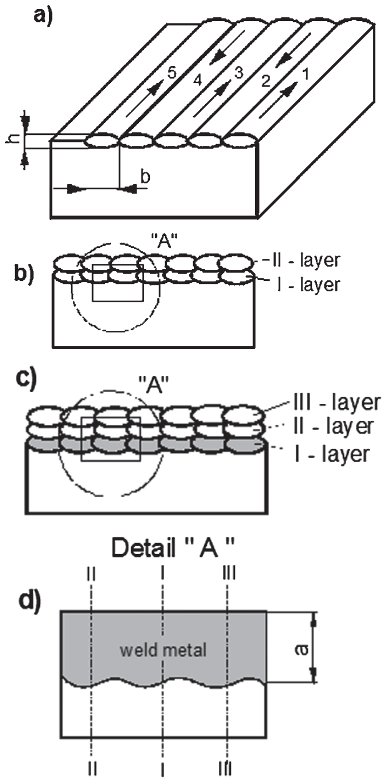
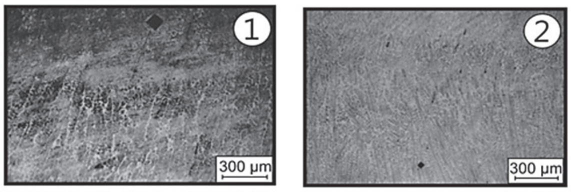


**Figure 1** Sequence of deposition: a–layer 1, b–layer 2, c–layer 3, d–metallographic ground slit [5]

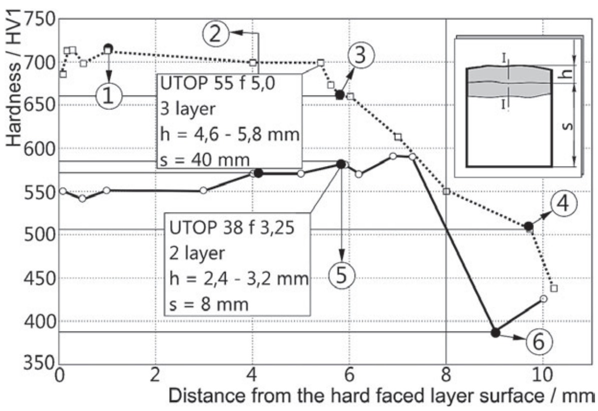
The same scheme was applied for other layers (Figures 1b and 1c). The width of the pass deposited by the electrode of diameter ∅ 3,25 mm was b ≈ 10 - 12 mm, the height was h ≈ 1,5 mm. For the electrode of diameter ∅ 5 mm parameters were b ≈ 10 - 12 mm and h ≈ 2,1 mm. The metallographic slit was the sample for microstructure determination and hardness measurement; Figure 1d [5]. Hardness was measured along three directions perpendicular to the hard faced layer (Detail A in Figure 1d – no layers are shown, just general "weld metal" zone). Hardness was measured in the base metal (BM) in the heat affected zone (HAZ) and in the weld metal (WM). Along a single line, hardness was measured at three points at least, for each of the zones. The first indent in HAZ ought to be as close as possible to the melding zone. In Figure 2 are shown results only for direction I-I.

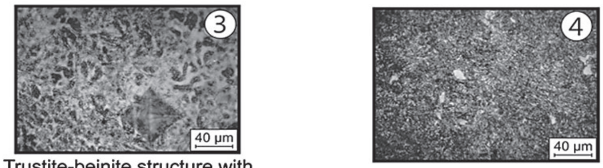
In Figure 2 are shown results only for direction I-I. Microstructure of characteristic zones of the two-layer weld metal obtained by electrodes UTOP 38 and UTOP 55 (Figure 2), does not significantly differ from the weld metal obtained by three-layer hard facing. Figure 2 gives diagrams of hardness measured at the cross section of the weld, as well as the microstructure of characteristic zones obtained by hard facing with two different electrodes. In both cases the samples were heated up to $T_p$ = 300 ºC before hard facing, and tempered at the temperature of $T_{tem}$ = 340 ºC afterwards.



Dendrite structure perpendiculary to the weld metal surface

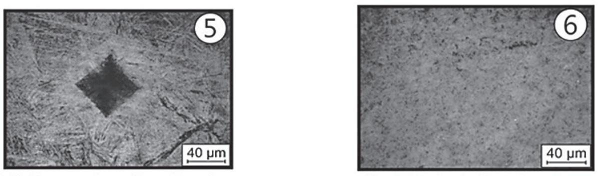
Dendrite structure predominantly oriented perpendiculary to the weld metal surface





Trustite-beinite structure with minor proportion of martensite

Tempered interphase structure



Beinite-martensite structure

Sorbite-beinite structure

**Figure 2** Hardness distribution and structure of characteristic zones for 56NiCrMoV7 [5]

## DETERMINATION OF THE COOLING TIME $t_{8/5}$

The cooling time can be determined from the measured temperature cycle curve, or using analytical, empirical or numerical temperature cycles calculation. The objective of authors was obtaining the temperature cycle during the hard facing enables reading-off the cooling time $t_{8/5}$. Authors analyzed results, which were obtained experimentally, empirically and numerically, for plates thicknesses 7,4 mm and 29 mm. The $t_{8/5}$ time was determined based on the Ito-Bessyo formula [11], Rikalin's formula and via the thin sheet limit thickness. Temperature cycles and the cooling time were measured on models with drilled holes, what guarantees that the cycles' determination would be as accurate as possible [5]. In Tables 5 and 6 the obtained results are presented.

Table 5 **Hard facing parameters: *s* = 7,4 mm: *I* = 115 A, *U* = 25 V, $q_{ef}$ = 2 300 W; *s* = 29 mm: *I* = 190 A, *U* = 28 V, $q_{ef}$ = 4 256 W [5]**

| Thickness/ mm | Rate $v_z$ / mm/s | Input energy $q_l$ / J/mm | Temperature $T_o$/ $T_p$ / ºC |
|---|---|---|---|
| 7,4 | 1,90 | 1 210,5 | 178 |
| | 2,08 | 1 105,8 | 180 |
| | 2,15 | 1 069,8 | 169 |
| 29 | 1,30 | 3 273,8 | 355 |
| | 1,61 | 2 643,6 | 231 |
| | 2,58 | 1 650,0 | 204 |
| | 1,67 | 2 541,4 | 178 |
| | 1,85 | 2 300,0 | 235 |

Table 6 **Cooling time $t_{8/5}$ comparative values [5]**

| Thickness/ mm | Cooling time $t_{8/5}$ / s | | | | Point/ Layer |
|---|---|---|---|---|---|
| | $(t_{8/5})^J$ | $(t_{8/5})^{Sgr}$ | $(t_{8/5})^{EXP}$ | $(t_{8/5})^R$ | |
| 7,4 | 22,8 | 100,3 | 23,0 | 48 - 54 | 11/1 |
| | 20,1 | 84,9 | 27,0 | 42 - 50 | 18/1 |
| | 18,2 | 73,4 | 19,5 | 36 - 43 | 3/1 |
| 29 | 76,2 | 287,5 | 78,0 | 70,5 - 74 | 16/1 |
| | 24,4 | 47,30 | 25,0 | 24-27 | 14/1 |
| | 10,4 | 14,89 | 12,0 | 13-14,5 | 6/1 |
| | 17,6 | 28,80 | 16,0 | 18-20 | 13/1 |
| | 20,2 | 37,10 | 20,5 | 21-23,5 | 21/1 |

The temperature cycles and the $t_{8/5}$ time were determined numerically, by the Finite Element Method (FEM). The obtained results for the characteristic case for each plate are presented in Table 7 and in Figures 3 and 4 [9].

Based on theoretical, experimental and numerical results, it was established that the calculated cooling time, within the critical temperature interval, could be the most accurately determined by the Ito - Bessyo formula [11]. It

Table 7 **Comparative values of $t_{8/5}$ [9]**

| Plate thickness, mm | | $s$ = 7,4 | $s$ = 29 |
|---|---|---|---|
| $q_l$ / J/mm | | 1 105,8 | 1 650 |
| $T_p$ / °C | | 180 | 204 |
| Cooling time $t_{8/5}$ / s | $(t_{8/5})^J$ | 20,1 | 10,43 |
| | $(t_{8/5})^{Sgr}$ | 84,9 | 14,89 |
| | $(t_{8/5})^{EXP}$ | 27 | 12 |
| | $(t_{8/5})^R$ | 42-50 | 13,5-14,5 |
| | $(t_{8/5})^{FEM}$ | 31 | 11,5 |

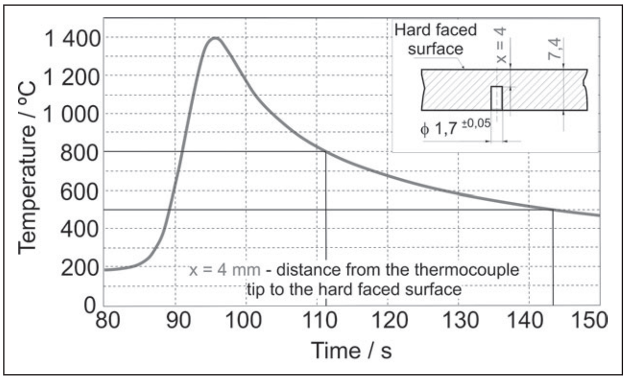


**Figure 3** FEM temperature cycle of HAZ hard faced layer ($s$ = 7,4 mm, $q_l$ = 1 105,8 J/mm, $v_z$ =2,08 mm/s, $x$ = 4 mm, $T_p$ = 180 °C) [9]

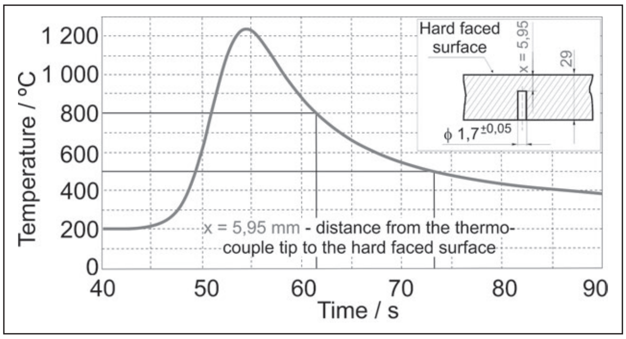


**Figure 4** FEM temperature cycle of HAZ hard faced layer ($s$ = 29 mm, $q_l$ =1 650 J/mm, $v_z$ =2,6 mm/s, $x$ =7,1 mm, $T_p$ =204 °C) [9]

was shown that the cooling speed could be accurately predicted without the expensive experimental procedures, which was one of the objectives of this paper.

## DISCUSSION AND CONCLUSIONS

Based on the presented results, one can conclude that the FEM provides the best conformity with the experiment and among empirical formulae the same goes for the expression of Ito-Bessyo, for the case of hard facing of planar and prismatic parts. By applying the specified information, the cooling time in critical temperature interval can be determined with sufficient accuracy, without complex and expensive experimental procedure. Typical results for the parameter $t_{8/5}$ are shown in Tables 5 - 6, based on data taken from Tables 1 and 2, as given for the optimal welding parameters, and including the FEM results for the same input data. By comparing the results shown in Tables 5, 6 and 7, the major (intolerable) differences are observed between the cooling time calculated according to formula $t_{8/5}$ = f($s_{gr}$) and experimental results, while the best accuracy with experimental results is achieved by numerical method and Ito-Bessyo formula. This conclusion refers to hard facing of the flat sheets, while other forms of hard faced surfaces are yet to be analyzed. Hardness results and analysis of microstructure revealed that the appearance of unfavorable purely martensitic structure was avoided; the microstructure was estimated as the tempered martensite and interphase tempering structures. Two important achievements were: 1. hardness of the hard faced layer was higher than that of the base metal (about 500 HV for the UTOP 38 electrode and about 700 HV for the UTOP 55 electrode). 2. Hardness in the HAZ, as the most critical zone of the hard faced layer, was reduced by tempering, while prior to heat treatment it was equal to hardness of the base metal.

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**Note:** Responsible person for English translation is: Radmila Paunović Štajn, Ph.D, Professor, University of Kragujevac, Serbia, Sworn Court interpreter for English language