DETERMINATION OF THE OPTIMAL TEMPERING TEMPERATURE IN HARD FACING OF THE FORGING DIES

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Resume

Here is analyzed selection of the optimal technology for heat treatment during the reparation of the damaged forging dies. Those tools are manufactured from alloyed tool steels for operation at elevated temperatures. Those steels are prone to self-hardening, so in reparatory hard-facing they must be preheated, additionally heated and tempered. During the tempering, in temperature interval 500-600°C, a secondary increase of hardness and decrease of impact toughness occurs, the so-called reversible tempering brittleness. Here is shown that it can be avoided by application of metallurgical and technological measures. Metallurgical measures assume adequate selection of steels. Since the considered steels are per se prone to tempering brittleness, we conducted experimental investigations to define the technological measures to avoid it. Tests on models were conducted: tempering from different temperatures, slow heating and cooling in still air. Hardness measurements showed that at 520°C, the secondary increase of hardness occurs, with drop of the impact toughness. Additional hard-facing tests included samples tempered at various regimes. Samples were prepared for mechanical and metallographic investigations. Results presented illustrate influence of additional heat treatment on structure, hardness and mechanical properties of the hard-faced layers. This enabled establishing the possibility of avoiding the tempering brittleness through technological measures.

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1. Introduction

The forging dies are in exploitation subjected to numerous cyclic loads, thus, after certain operating time, the impression damages occur, and the tool has to be replaced or repaired [1-4]. The main causes of damaged dies withdrawal from exploitation could be: change of dimensions and form of impressions due to friction and wear, cracks all over the die due to thermal fatigue, and micro cracks caused by action of the stress concentrators.

Factors that are leading to thermal fatigue at elevated temperatures are: material thermo-physical characteristics (thermal conductivity, specific heat and coefficient of thermal linear extension), the geometry of part (size, shape, type of surface), and other material properties (mechanical, chemical, structural) [5, 6].

Some of the reasons for failure occurrences are: increase of the forged pieces dimensions due to worn die, deformation of the thin-walled portions of the die (ribs, mandrels), appearance of cracks at certain parts of the die, local fractures etc.

In order to select the optimum technology of forging dies hard facing, numerous tests were conducted at the model whose sizes were determined according to the similarity theory principle, namely the non-dimensional analysis.

Manufacturing of the new dies made of construction carbon steels, with working surfaces hard faced by the tool steel, presents an exception.

2. Materials for forging dies manufacturing and their characteristics

Refractory steels are used for temperatures above 300 °C. Here we are talking about small, eventually medium and large dies for hot forming, tools for pressing and extrusion of non-ferrous metals at elevated temperatures, tools for hot trimming, dies used for pressurized casting of pure Al, Zn and Mg.

In the considered case, all experiments were conducted on forging dies made of steel Č5742 (DIN 17350: 56NiCrMoV7, EN 10027-2: 12174) and Č4751 (DIN 17350: X38CrMoV51, EN 10027-2: 12343). Chemical composition, mechanical characteristics and microstructure of those steels are given in Tables 1 and 2 [5].

On selected samples (models) we have measured hardness after the heat treatment and it was 40-42 HRC for Č5742 and 41-49 HRC for Č4751. Since the samples of the thicker cross sections, which were also hard faced (s = 40-45 mm), were made of steels prone to self-hardening (C > 0.35 %), the preheating was necessary. The preheating temperature was determined according to Seferian formula, and has value $T_p \approx 300$ °C.

3. Selection of procedure, technology and filler material

Technological parameters of hard facing were determined according to [5-8], and hard facing was performed in two and three passes to decrease the degree of mixing (dilution). As a filler material we applied highly alloyed basic electrodes UTOP 38 (DIN 8555 E3-UM-40T, ϕ3.25 mm) and UTOP 55 (DIN 8555 E6-UM-60T, ϕ 5.00 mm) [7-10]. The filler materials were aimed for hard facing of dies that are used for forming of steels and other metals, both in hot and cold state. Hard-faced layers are tough, resistant to wear and impact. The hard faced layers hardness is constant up to temperature of 600 °C.

These basic electrodes were dried prior to application according to the following regime: heating up together with the furnace up to temperature of 350 - 400 °C, keeping for 2 hours at the drying temperature, and cooling in the furnace for 1 hour, while the temperature did not fall below 150 °C. Thus heated electrodes were used for hard facing of the preheated samples, with eliminated possibility of appearance of hydrogen induced cracks.

Table 1

Chemical composition and comparative marks of steels Č5742 (DIN 17350: 56NiCrMoV7, EN 10027-2: 12174)and Č4751 (DIN 17350: X38CrMoV51, EN 10027-2: 12343)

No.	Mark by YUS	Chemical composition, %									Relation to other standards	
		C	Si	Mn	P	S	Cr	Ni	Mo	V	DIN	UNI
1.	Č5742	0.55	0.3	0.7	0.035	0.035	1.1	1.7	0.5	0.12	56NiCrMoV7	U52NiCrMo6KU
2.	Č4751	0.40	1.0	0.4	0.025	0.025	5.0	-	1.3	0.4	X38CrMoV51	UX35CrMo05KU

Table 2

Mechanical characteristics and microstructure of steels Č5742-JUS (DIN 17350: 56NiCrMoV7, EN 10027-2: 12174) and Č4751-JUS (DIN 17350: X38CrMoV51, EN 10027-2: 12343)

No.	Mark by YUS	Soft annealing			Tempering			Preheating temperature T_p (°C)	Microstructure BM
		T (°C)	HV_{max}	R_m (MPa)	T (°C)	HRC	R_m (MPa)		
1.	Č5742	670-700	250	850	400-700	50-30	1700-1100	≈ 300	M + B (Interphase)
2.	Č4751	800-830	250	850	550-700	50-30	1700-1100	≈ 300	M + B (Interphase)

In Tables 3 and 4 are presented the hard facing parameters (hard facing current was for about 10 % lower than at welding), as well as properties of the filler material [5, 7, 8].

Deposition of hard faced layers is realized in several passes (Fig. 1). The width of a pass, hard faced with the ϕ 3.25 mm electrode, was b ≈ 10-12 mm, the height of each hard faced layer was h ≈ 1.5 mm, and for the ϕ 5.00 mm electrode measures were b ≈ 16-18 mm and h ≈ 2.1 mm.

4. Phenomenon of tempering brittleness of the hard faced forging tools

4.1. Theoretical considerations

During the hard facing of hardening prone steels, aimed for forging dies, in the vicinity of the hard faced layer appear brittle unfavorable structures, the residual stresses increase occurs, which frequently surpass the yield strength. From all these reasons, it is necessary to perform tempering after the forging dies hard facing, in order to decrease the level of residual stresses, and to transfer martensite structures into the upper bainite (feathery) structures (or the inter-phase structures), with preservation of good mechanical properties.

It was noticed that, in some steels alloyed with Mn or Cr, i.e., Cr-Mn or Cr-Ni, during tempering can appear a damaging phenomenon – the so called "tempering brittleness" (hardness increase, toughness and dilutability decrease). In cases when tempering is performed from higher temperatures, the rapid cooling is recommended through the critical temperatures

Table 3

Parameters of the MMA hard facing (HF)

No.	Electrode mark SŽ "Fiprom"	Electrode mark DIN 8555	Core diameter (mm)	HF current (A)	Voltage (V)	HF velocity (cm/s)	Heat input energy (J/cm)
1.	UTOP 38	E3-UM-40T	3.25	115	26	≈ 0.28	8543
2.	UTOP 55	E6-UM-60T	5.00	190	29	≈ 0.25	17632

Table 4

Filler material properties [14]

No.	Electrode mark SŽ "Fiprom"	Electrode mark DIN 8555	Chemical composition, % C	Cr	Mo	V	W	Type of current	HF layer hardness HRC	Application
1.	UTOP 38	E3-UM-40T	0.13	5.0	4.0	0.20	+	= (+)	36-42	HF of dies for elevated and normal temperatures
2.	UTOP 55	E6-UM-60T	0.50	5.0	5.0	0.60	+	= (+)	55-60	ibid

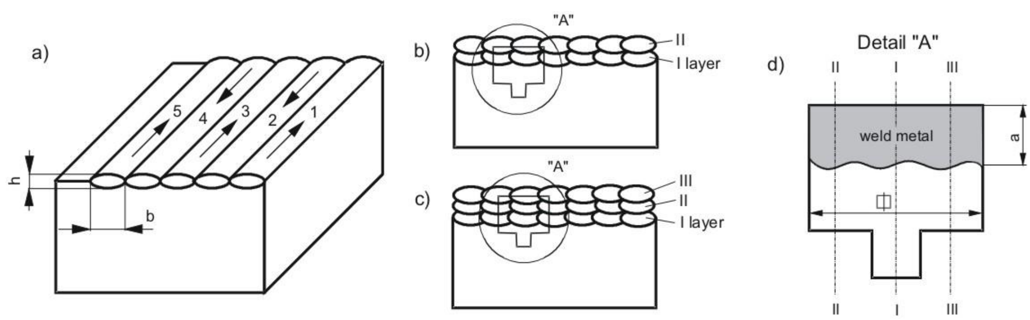


Fig. 1. Order of hard-faced layers deposition: a - 1st layer, b - 2nd layer, c - 3rd layer; d - pin appearance

region, i.e., under-cooling, what prevents diffusion as an essential factor for appearance of tempering brittleness [5, 11-13].

On the other hand, for some classes of steels, the decrease of toughness can also be noticed by metallographic methods [5], while for reduction of risk for this phenomenon to occur, it is strongly recommended to alloy these steels by molybdenum (up to 0.6 %), by tungsten (up to 1.5 %), as well as by niobium. During tempering, these elements exhibit positive effects, since they are slowing down the segregation process. On the contrary, carbon and phosphorus contribute to appearance of the tempering brittleness. The assumption is that the negative effects of phosphorous already start at small amounts (about 0.005 %) [5]. Influence of phosphorus is related to its expressed tendency to segregation. Also, the fact that carbides, extracted from steel in the brittle condition are richer with phosphorus than carbides extracted from steels that possess normal toughness, speaks of a very important influence of phosphorus on this phenomenon.

Sensitivity of material to tempering brittleness can be established by testing the steel for impact toughness, in the wide temperature range, as well as by determination of the steel transition temperature from ductile to brittle fracture. Tendency of different steels to exhibit the tempering brittleness depends mainly on their chemical composition, as well as on manufacturing procedure and processing.

4.2. Presentation of obtained results

To examine influence of the tempering temperature of hard-faced tools on hardness distribution across the hard-faced layer cross section, we have varied tempering temperatures from 370 to 670 °C, taking 30 °C as the temperature interval. Period of keeping the sample at certain temperature was two hours, with slow cooling down to room temperature. In Fig. 1 are presented hard faced layer and base metal (BM) hardness variations as a function of the tempering temperature. Function of hardness variation of the hard faced layer, obtained by experiments, is in agreement with data from literature for the base metal [5], since the chemical composition of the filler material approximately corresponds to that of the base metal.

In order to investigate the cooling speed influence on the tempering brittleness, we heated new samples up to 520 °C, then heated through for two hours, and cooled slowly, in one case together with the furnace, and in the other in the still air. The HV1 hardness was measured on those samples in various directions, as shown in Figure 1, starting from different distances from the hard-faced layer's surface. Diagrams as representation of the hardness variation of the hard faced layers' characteristic zones are given in Figure 2.

5. Determination of mechanical properties, hardness and microstructure for various cases of additional tempering

In order to determine mechanical properties, hardness, and microstructure for various various cases of additional heat treatments of tool steel a set of new samples has been prepared, as models with dimensions 100×100×29 mm-6 pieces (made of steel Č5742), all cut out from the same plate. Five samples are then preheated to $T_p \approx 350$ ºC and hard faced with dried electrodes E6-UM-60T-ϕ 5 mm in three layers, whereas the sixth sample was used for preparation of samples for determination of the base material mechanical properties.

Samples are treated in different regimes as shown in Figure 3. After the heat treatment, the hard faced part was polished and samples were prepared from the plate according Figure 4. To determine the impact toughness, it was necessary to prepare the DVMK testing samples with dimensions 6×6×44 mm, with the U notch which was 2 mm deep and 1.5 mm wide, according to DIN 50115, whereas for the tension tests test samples with dimensions 10×4×100 mm were prepared.

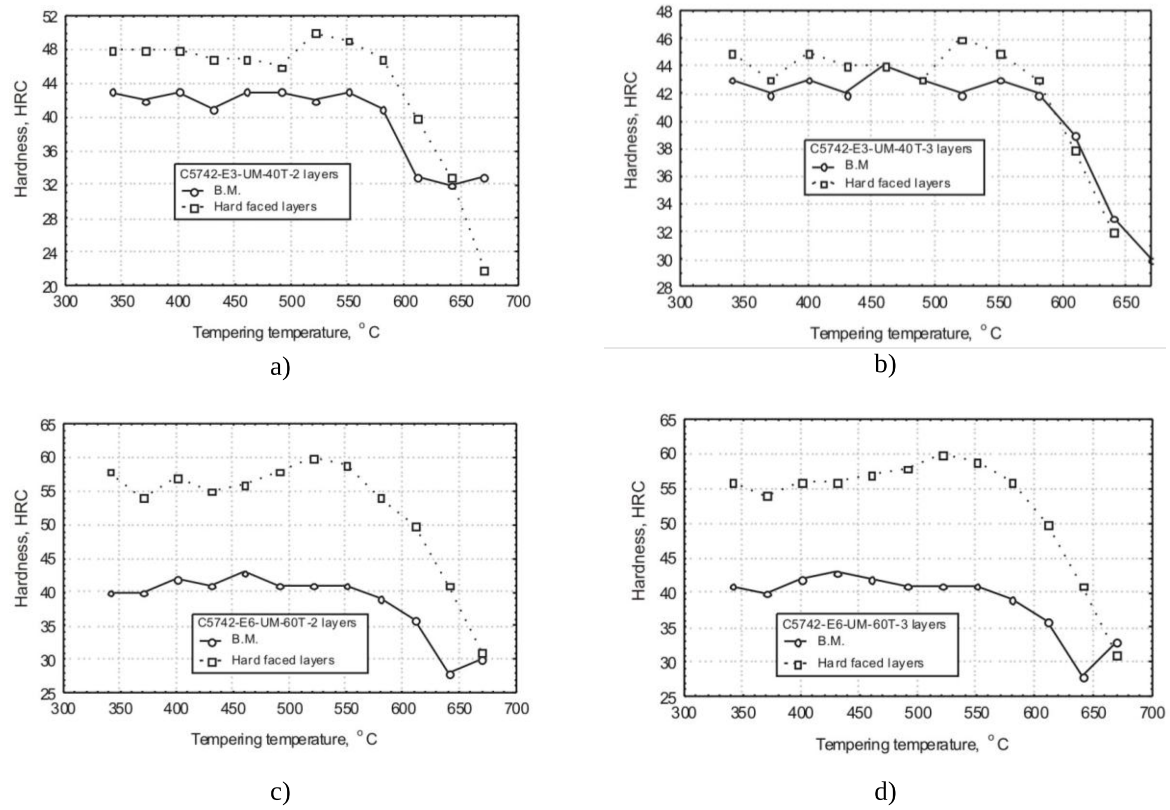


Fig. 2. Hardness variation as a function of tempering temperature

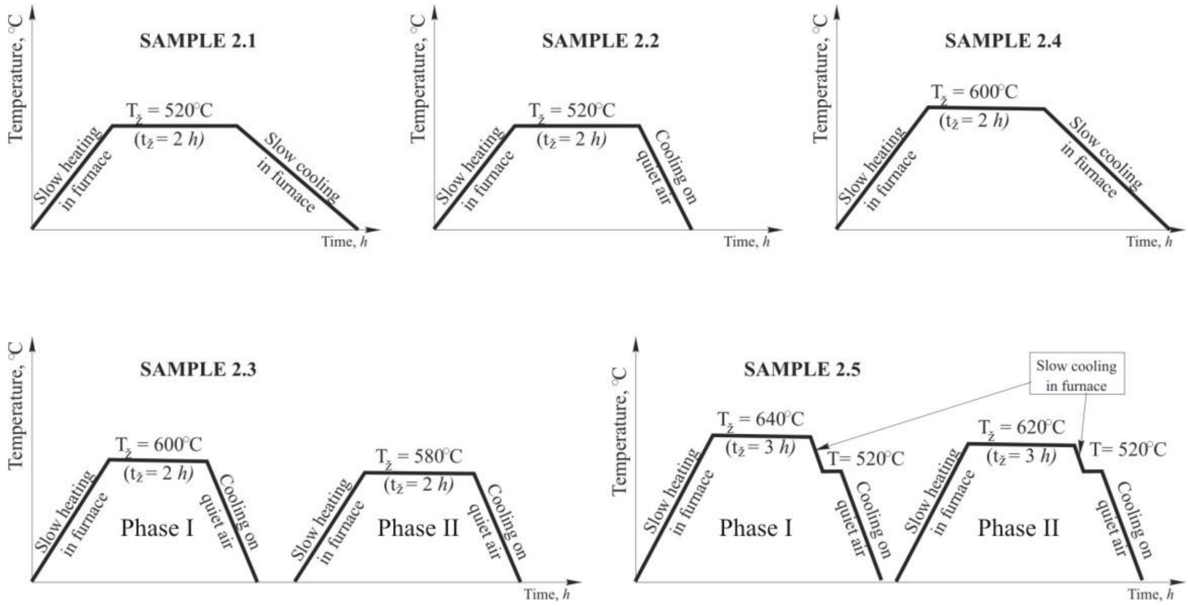


Fig. 3. Various regimes of additional heat treatment - tempering [5]

Hard facing microstructure of samples was as follows: for samples 2.1 and 2.2 – martensite-bainite; for sample 2.3 – martensite; for samples 2.4 and 2.5 – martensite with interphase. Microstructure of the heat affected zone (HAZ) and the base metal (BM) was interphase structure for all the samples. In Figure 5a is presented the microstructure of the hard faced layers and in Figure 5b the microstructure of the HAZ of sample 2.5 [5].

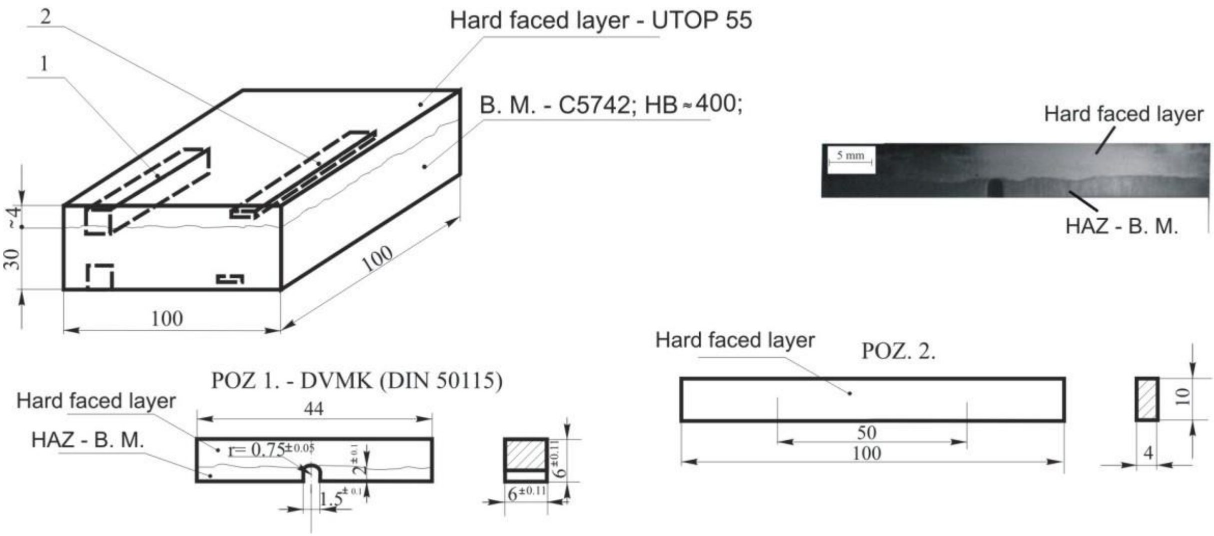
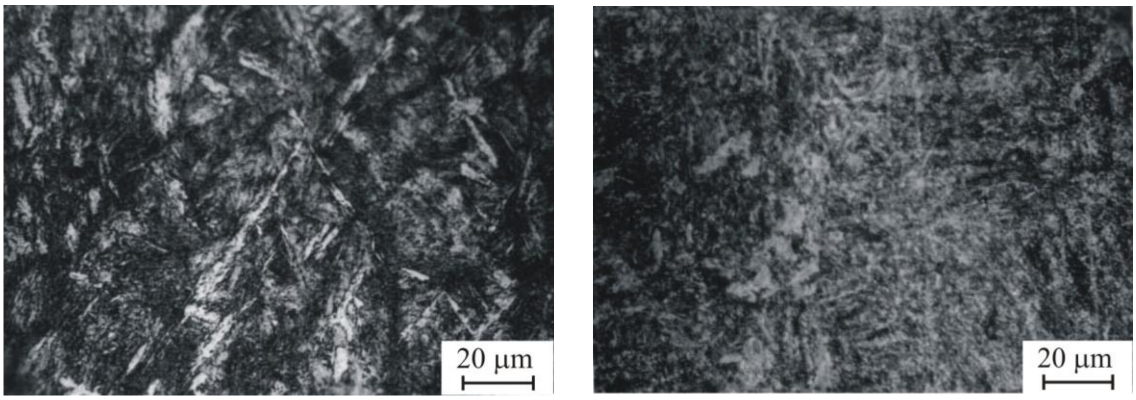


Fig. 4. Method of samples preparation from the hard faced plate [5]



a) Hard facing b) HAZ

Fig. 5. Microstructure of hard facing and HAZ (sample No. 2.5)

Hardness variation in characteristic cross sections is given in [5]. Detailed considering of hardness variation, in relation to applied additional heat treatment-tempering, leads to the conclusion that: hardness in the hard faced zone decreases as tempering temperature increases, i.e., plastic properties increase at account of the strength decrease. Similar behavior may be noticed in the base material, whereas hardness of the HAZ also decreases. This may be explained by the well known effect of tempering of previously hardened zones during the multiphase hard facing. Namely, parameters of certain hard faced layers and their cross sections must be chosen in such a way that volume surrounded with isotherm of 700 ºC overlays the previously tempered zones. The latest layer is partly polished to represent real conditions and to comply with recommendations [5].

5.1. Tension tests

After the heat treatment – tempering with polishing, according to Figure 3 – testing samples and metallographic slices were prepared (Fig. 4). Tension tests are performed in authorized laboratory "Zastava" in Kragujevac on hydraulic tension test device A. J. Amsler with force range 0 – 10000 daN. Testing results are shown in Table 5.

Obtained results correlate hardness and tensile strength in the case of base metal in expected way, whereas in the case of specimen made of pure hard faced material such a correlation was not obtained. In such cases, values of tensile strengths are notably lower. Increase of tempering temperature causes increase in plastic properties. Since forging dies predominantly carry pressure loads, and less tensile loads, achieved values of tensile strength satisfy required working conditions.

Table 5

Tension tests results [5]

Sample No.	Test samples dimensions			F_{eH} (N)	F_m (N)	Yield Strength, R_{eH} (MPa)	Tensile strength, R_m (MPa)
	Width, b (mm)	Thickness, s (mm)	Cross section, S_0 (mm^2)				
2.1	10.5	3.99	41.850	Not registered	-*)	-	-
2.2	10.8	4.03	43.524	Not registered	29200	-	671
2.3	11.0	3.99	43.890	Not registered	31000	-	706
2.4	10.5	3.99	41.895	Not registered	32000	-	764
2.5	10.3	3.99	41.097	Not registered	37200	-	905
B.M.	10.9	4.22	45.998	38694	47400	841	1030

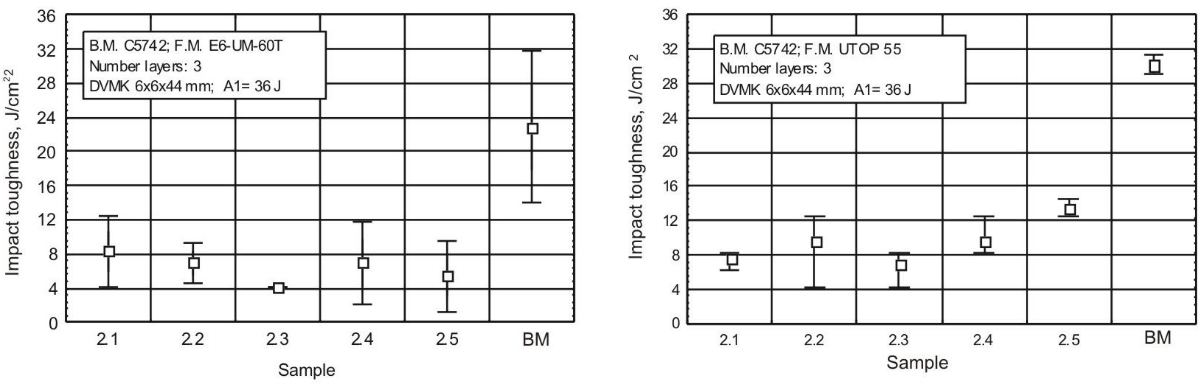
*) Unreliable data, due to defects observed in the hard faced layer.

5.2. Impact toughness testing

The complexity of working conditions of forging dies and cyclical changes of impact-pressure loads, as well as temperatures in contact zones, were already underlined in introduction. That caused problem in selecting the working temperatures. Earlier research [5] presented dependence of the contact temperature changes in terms of the forging insert heating level, temperature of preheated tool, as well as of the forging type (hammer, press etc.). There the impact toughness has been determined for specimens tempered in various ways, both at room temperature (T_{test} = T_{rt} = 20 ºC) and at working temperature (T_w = 566 ºC). The prepared specimens were tested with the Charpy pendulum with available energy of 36 J. Three sets of tests were performed for each set of the heat treatments. In Figs. 6a and 6b is shown obtained toughness per unit area.

6. Discussion

Experimentally obtained results and their analysis show that path to avoid or decrease effect of "tempering brittleness", typical for tool steel for work at elevated temperatures in the interval 500 – 520 ºC. Complete machine tooling for preparation of specimens was grinding and polishing. Additional difficulty arose from the fact that it was necessary to determine properties of all the zones of the considered model, such as hard faced layers, joining zones, heat affected zone and base material. Especially significant was to establish zones of minimal toughness after the additional heat treatment since the brittle fracture in production conditions starts from those zones.



a) T_{test} = 20 ºC b) T_W = 566 ºC

Fig. 6. Maximum, minimum and mean values of toughness of various tempered samples

Observed differences of obtained results in mechanical testing, show that is necessary to have proper selection of the hard facing technology, which has a crucial influence on the hard facing output properties.

Analysis of experimentally obtained results of impact toughness both at room and elevated temperatures, showed the increase of toughness with increase of the tempering temperature. A significant difference of obtained results, with respect to properties of the base metal was noticed, what was to be expected due to ways of obtaining the multi-layered hard-faced deposit and possible errors in hard-facing.

Based on all the obtained results, one can conclude that the version 2.5 provides for the smallest results dissipation, especially at the operating (elevated) temperatures. This could be one of the indicators for the final selection of the optimal (the most favorable) tempering regime, in order to completely avoid the unwanted phenomenon of tempering brittleness.

7. Conclusion

The heat treatment influence on output – useful properties of the hard-faced forging dies was shown in this paper. By varying the different tempering regimes we have established the principle of the hardness variation, monitored the micro structure variation and determined mechanical properties and impact toughness of the pure hard-faced layer at room temperatures.

Experimentally obtained results show that during the hard-faced models tempering, at temperature of approximately 520 °C, a phenomenon of secondary hardness increase occurred, while all the other properties, significant for reliable operation of the tool, were mainly satisfactory. In that sense we established the tempering regime, by which one obtains some of the hard-faced layers' properties (hardness, micro structure, tensile strength and impact toughness) very close to respective properties of the base metal.

Analysis of experimental investigations points to a very complex way of how to avoid or minimize the tempering brittleness effect, characteristic for tool steels that operate at elevated temperatures, within the interval 500 – 520 °C. We showed that by the proper selection of a tempering regime, one can avoid this unwanted phenomenon through technological measures. We also illustrated the possibility of avoiding the tempering brittleness through metallurgical measures, as well as the fact that this phenomenon is reversible.

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Note

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