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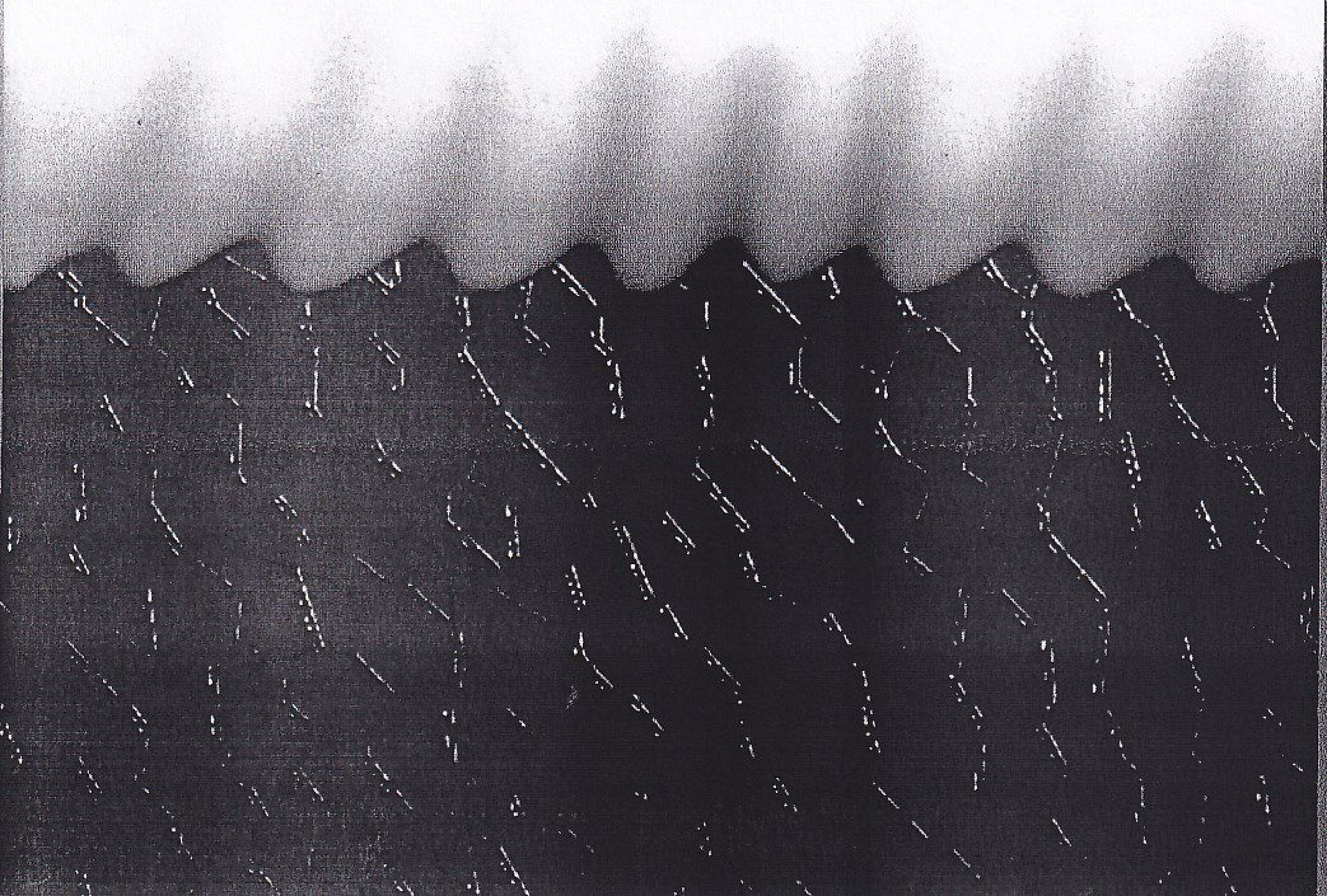

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Slovak Republic

tel.: 00421- 41 - 513 2614
fax: 00421- 41 - 565 2940
e-mail: redakcia.mi@fstroj.uniza.sk

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DETERMINATION OF THE COOLING RATE AND ITS INFLUENCE ON THE HARD-FACED FORGING DIES PROPERTIES

Vukić Lazić[1], **Aleksandar Sedmak**[2], **Božidar Krstić**[1], **Ružica Nikolić**[1*], **Srbislav Aleksandrović**[1], **Rajko Čukić**[1]

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Resume

In the paper is pointed to operating conditions of the forging dies, properties of the hard-faced materials, methodology of choosing the optimum technology of hard facing and filler materials. Presented are, as well, the experimental results of testing the influence of the hard facing regime on the output characteristics of the hard-faced forging dies. The cooling rate in the critical temperature interval was determined primarily, and her influence on hardness and microstructure was monitored, i.e., the relationship was established between the input and output characteristics through the corresponding (available) transformation diagrams for the given steel.

Keywords: *Hard-facing, cooling rate, forging dies, microstructure.*

1. Introduction

The forging dies are in exploitation subjected to numerous cyclic loads at elevated temperatures, so after certain operating time, the impression damages occur, and the tool has to be replaced or repaired. Statistical investigations of the damaged dies [3, 6] have shown that main causes of their removing 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.

Wear, caused by action of impact-compressive loads, is characterized by appearance of deformation and increased friction, as well as cracks at a certain depth on working surfaces. The fatigue cracks may also appear, also at certain depth beneath the surface.

Wear that appears at elevated temperatures is a consequence of oxidation, forming of oxide coating at high temperatures, worsening of the mechanical characteristics at surface layers, what, together with effects of thermal fatigue, leads to increase of stresses and finally to destruction of surface. Accelerated wear of die surfaces that operate at elevated temperatures is usually in form of characteristic cracks and even crumbling caused by thermal fatigue. Factors that are leading to thermal fatigue are material thermo-physical characteristics (thermal conductivity, specific heat and coefficient of thermal linear extension), the part geometry (size, shape, type of surface), and other material properties (mechanical, chemical, structural).

The thermal stresses, caused by the temperature gradient, also impose negative influence, as well as the structural stresses, which depend on chemical composition of steel and kinetics of austenite transformation, namely the cooling speed. Due to influence of cyclic variation of thermal stresses, the initial cracks can also appear on the material surface.

Through analysis of physical properties changes of the tool steels during the thermal-mechanical fatigue, it was established that material destruction occurs in three phases: at first the material strength is decreased, then the pile-up of dislocations appear, and finally the crack is initiated. In the first phase the temperature causes relaxation, what in turn, causes decrease of strength and hardness of steel, as well as an increase of the carbides share and their coagulation. During the second phase a process of plastic deformation develops, what causes material hardening. In the third phase the decisive influence has the coagulation of carbides and pile-up of crystal lattice defects, what causes initial cracks to develop from already existing voids and micro-cracks. If there exists a possibility for action of the dislocation mechanisms for creation of the fatigue cracks, then in numerous cases, initiators of such cracks are the surface scratches, material faults of technological

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V. Lazić; B. Krstić; R. Nikolić; S. Aleksandrović; R. Čukić – Faculty of Mechanical Engineering, University of Kragujevac, Sestre Janjic 6, 34000 Kragujevac, Serbia.

A. Sedmak – Faculty of Mechanical Engineering, University of Belgrade, Bulevar Kraljice Marije 16, 11000 Belgrade, Serbia.

Corresponding author, e-mail address: ruzicarnikolic@yahoo.com

origin (forged in oxides, micro-cracks on the inter-phases boundaries of the hard phases and the plastic substrate, non-metallic inclusions, brittle phases) [1, 2, 4, 6].

In the concrete case, we analyzed the forging dies aimed for manufacturing parts in car and trucks making industry. During the excessive monitoring of dies in exploitation, it was noticed that failures (removing dies form exploitation) could be due to following reasons:

- 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, and
- local fractures.

2. Materials for manufacturing dies aimed for operation at elevated temperatures and their properties

Here we speak of tools that operate at elevated temperatures of up to 600°C and which are exposed to higher static pressures and impact loads. Additions of Cr, W, V and Mo, as well as the increased content of carbon, provide for good weldability needed for larger cross sections of tools and high hardness at elevated temperatures [1].

As the most frequently applied materials here are presented two typical forging dies steels Č5742-YUS -56NiCrMoV7-DIN and Č4751-YUS-X38CrMoV51-DIN, aimed primarily for casting tools of nonferrous metals. Given steels are mostly used in Blacksmith shop of the "Zastava" factory. Chemical composition, mechanical characteristics and microstructure of these steels are given in Tab. 1 and Tab. 2.

Since the Blacksmith shop of the "Zastava" factory uses forging dies in thermally tempered state (quenching and high relaxation), we subjected all the samples to that treatment, to come as close as possible to real (exploitation) conditions. On selected samples - models we measured hardness after thermal treatment and it was 40-42 HRC for Č5742. These samples (of thickness 7.4 and 29 *mm*) were hard faced after preheating, due to fact that the aforementioned steels are prone to self-hardening (C>0.35%). The preheating temperature was determined by calculation according to the Seferian formula [2, 5, 7], and it ranged from T_p = 286°C to T_p = 305°C, for s = 29 *mm*. We adopted that $T_p \approx 300$°C [9, 10]. Real preheating temperatures were determined by measurement prior to start of hard facing.

By investigation of forging dies steels we came up with the conclusion that the lowest resistance to thermal fatigue, in the temperature range between 200 and 760°C, have materials with higher content of tungsten; substitution of this alloying element by molybdenum improves steel's resistance to cracks. Chromium also improves steels resistance to a degree that depends on the content of tungsten. Alloying by nickel usually does not contribute to increase of resistance to thermal fatigue. Resistance of steel to thermal fatigue is decreased with increasing of the carbon content (C > 0.3 %). Manganese mainly improves resistance to thermal fatigue [1, 3, 7].

Tab. 1

Chemical composition and comparative marks of steels Č5742 and Č4751

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	X38CrMoV5	UX35CrMo05K

Tab. 2

Mechanical characteristics and microstructure of steels Č5742 and Č4751

No.	Mark by YUS	Soft annealing			Relaxation (Tempering)			Preheating temperature T_p, °C (Seferian formula)	Microstructure B. M.
		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 (inter-phase)
2.	Č4751	800-830	250	850	550-700	50-30	1700-1100	≈ 300	M + B (inter-phase)

3. Choice of technology and filler materials

Hard facing of selected samples was done in the Laboratory for machine materials and technology at Faculty of Mechanical Engineering in Kragujevac with application of the cored electrodes. Technological parameters of hard facing were determined according to [2, 5], and hard-facing was performed in one, two and three passes to estimate the influence of mixing (dilution), and to establish in which pass the declared characteristics supplied by the manufacturer of electrodes were obtained. The velocity of hard facing during each pass was measured, and also, prior to applying another layer, the preheating temperature was checked, i.e., the interpass temperature. The digital-measuring device Tastotherm D1200 was used for measurements (which is supplied with a thermocouple NiCr-NiAl with a measuring range from - 50°C to 1200°C).

As the filler material were applied highly alloyed basic electrodes UTOP 38 (E3-UM-40T Ø3.25 *mm* - DIN 8555) and UTOP 55 (E6-UM-60T Ø5.00 *mm* - DIN 8555). They are aimed for hard facing of tools like: 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, like ingot mold, steel molds, dies and pressing mandrels. Hard-faced layers are tough, resistant to wear and impact. The hard faced layers hardness is constant up to temperature of $T_{pop} \approx 570°C$ [4], and according to recommendations by the supplier up to 600°C [11-SŽ-Fiprom].

Prior to application, the electrodes were dried according to the following regime: heating up in 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 what the level of diffusive hydrogen was decreased and the possibility for appearance of hydrogen induced cracks was eliminated.

In Tab. 3 and Tab. 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 [11-SŽ-Fiprom].

Tab. 3

Parameters of the AW hard facing

No.	Electrode mark		Core diameter, d_e, *mm*	Hard facing current, I, *A*	Voltage, U, *V*	Hard facing velocity, v_z, *cm/s*	Input heat, q_l, *J/cm*
	SŽ Fiprom	DIN 8555					
1.	UTOP 38	E3-UM-40T	3.25	115	26	0.241-0.136	9543-16911
2.	UTOP 55	E6-UM-60T	5.00	190	29	0.257-0.130	16912-32738

Tab. 4

Filler material properties

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

Order of applying the layers is given in Fig. 1a, and prior to application of the new layer the dross was removed with steel brush. According to this scheme other layers were applied too (the second (Fig. 1b) and the third (Fig. 1c)).

The pass width hard faced by the Ø 3.25 *mm* electrode was b ≈ 10-12 mm, and the hard faced layer height was h ≈ 1.5 mm, and for the electrode Ø5.00 *mm* the measures were b ≈ 16-18 *mm* and h ≈ 2.1 *mm*.

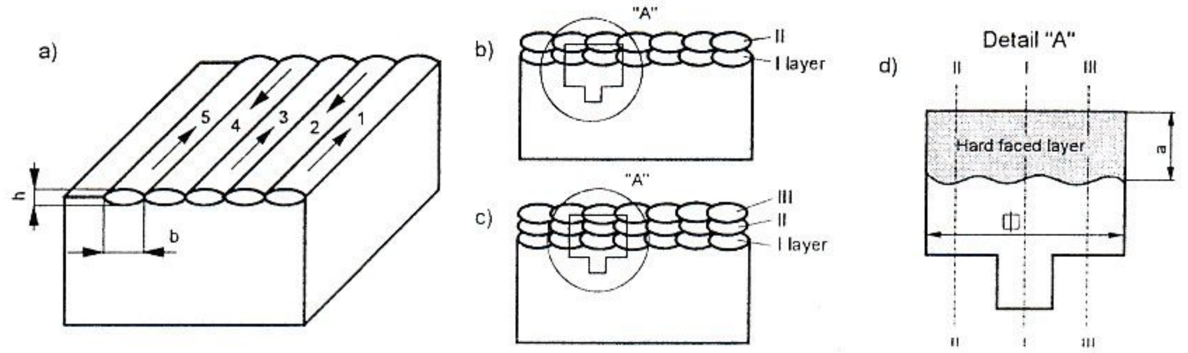


Fig. 1. Order of application of the hard-faced layers: a - 1 layer, b - 2 layers, c - 3 layers

4. Determination of the cooling time between 800 and 500°C - $t_{8/5}$

In hard facing of steel Č5742 it is not sufficient to take care only about technological parameters, which provide for regular forming of hard faced layer, but one also has to take into account the negative effect of the heat induced during the hard facing. This is why for these steels one must also take into account the influence of the temperature cycles on the increase of hardness in the heat affected zone, change of mechanical properties and tendency towards appearance of cracks. The main characteristics of the temperature cycles are: *maximum temperature, time of holding above the A_{C3} temperature and cooling rate at the least stability of austenite temperature.*

Optimum parameters of the hard facing technology are determined from the condition that the cooling temperature and the time of holding above the A_{C3} temperature ought to be within limits that provide for the best achieved properties of the hard faced layer.

For determination of the cooling rate, in literature exist certain analytical expressions, but from practical reasons, instead of the cooling rate the cooling time between 800 and 500°C - $t_{8/5}$ is given. Equations (1), (2) and (4) give the most frequently applied formulae for the cooling time $t_{8/5}$.

(a) Calculation of $t_{8/5}$ according to the thin sheet limit thickness ($t_{8/5}=f(s_{gr})$) [2, 7, 8, 9]

- for *thin sheets* ($s < s_{gr}$)

$$t_{8/5} = \frac{q_l^2 \cdot N_2}{4 \cdot \pi \cdot \lambda \cdot \rho \cdot c \cdot s^2} \cdot \left[\left(\frac{1}{500 - T_o} \right)^2 - \left(\frac{1}{800 - T_o} \right)^2 \right] \quad (1)$$

- for *thin sheets* ($s < s_{gr}$)

$$t_{8/5} = \frac{q_l \cdot N_3}{2 \cdot \pi \cdot \lambda} \cdot \left(\frac{1}{500 - T_o} - \frac{1}{800 - T_o} \right) \quad (2)$$

$$s_{gr} = \sqrt{\frac{q_l \cdot N_3}{2 \cdot \rho \cdot c} \cdot \left(\frac{1}{500 - T_o} + \frac{1}{800 - T_o} \right)} \quad (3)$$

(b) Calculation of - $t_{8/5}$ according to the Japanese authors formula [8]

$$t_{8/5} = \frac{k \cdot q_l^n}{\beta \cdot \left(T_{sr} - T_o \right)^2 \cdot \left[1 + \frac{2}{\pi} \cdot arctg \left(\frac{s - s_o}{\alpha} \right) \right]} \quad (4)$$

Data needed for calculation of the cooling time $t_{8/5}$, according to expressions (1), (2) and (4) are given in corresponding literature [2, 7, 8, 9].

For calculation of the cooling time several expression were derived, and they give large differences in results. Due to that we estimated accuracy of the previously cited expressions (1), (2) and (4) taking into account the following: *thickness of the hard-faced plates, input heat of hard facing and preheating temperature.*

The temperature cycle can be determined experimentally and computationally. From the experimentally obtained cycle directly is red off the $t_{8/5}$ time, which serves for evaluation of empirical expression accuracy, namely for estimation of the newly created structure and hardness of the HAZ.

Model-samples for experimental investigations we re prepared according to Fig. 2. Scheme of temperature measurement with help of thermocouples is given in Fig. 3. Besides the coated thermocouple of the known characteristics (type "K", of the "Philips" company), we used hand-made thermocouples of diameters ∅ 0.25 and ∅ 0.40 *mm*, whose characteristics (Fig. 4) was determined by calibration on different temperatures. Temperature cycles were determined in conditions without preheating and with preheating, by variation of the hard facing parameters. Results of measurements for the thin and thick sheet are given in tab. 5 and Tab. 6.

Characteristic temperature cycles are presented in Fig. 5a and 5b.

Through analysis of results presented in tab. 5 and Tab 6 one can notice unacceptable errors in the cooling time according to formula $t_{8/5} = f(s_{gr})$, while the best agreement with experimental results provide the formula of Japanese authors [4, 8, 9, 10]

The obtained conclusion refers to hard facing of plane sheets, while we did not yet investigate other forms of the hard faced surfaces

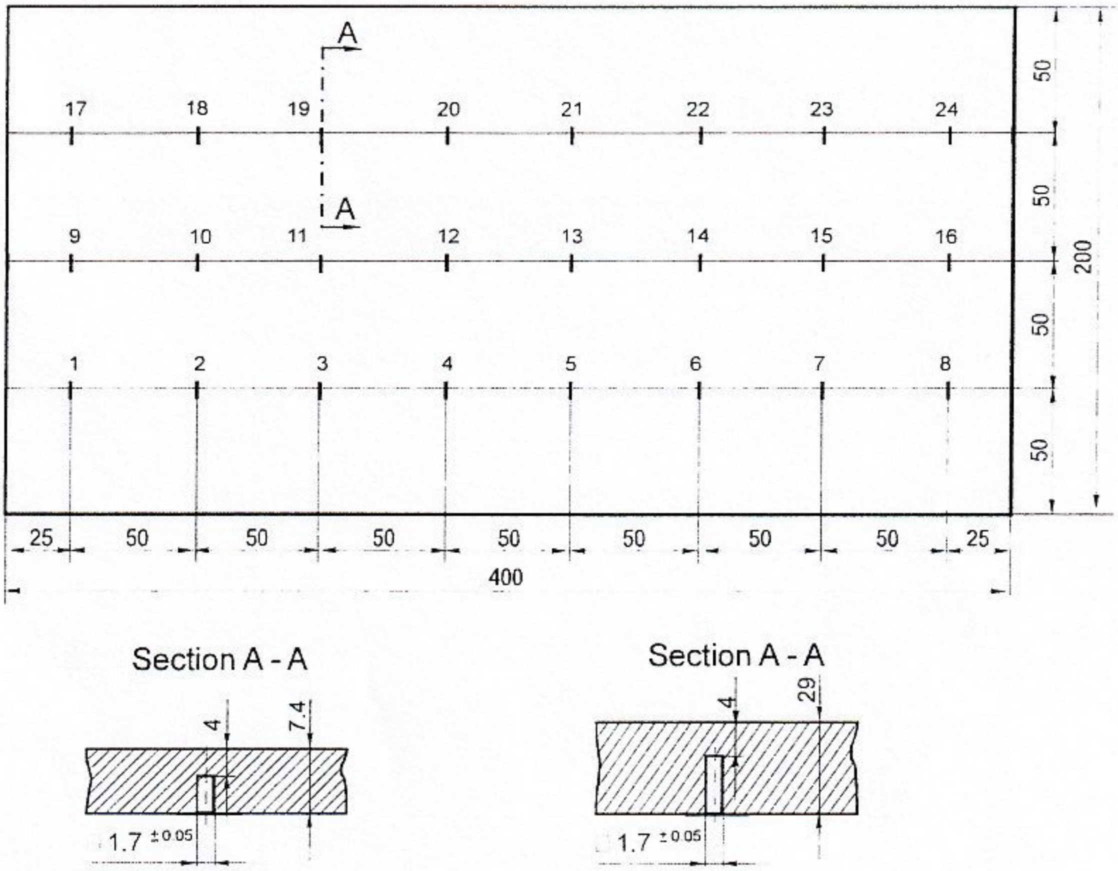


Fig. 2: Appearance of the model-sheet for temperature measurement

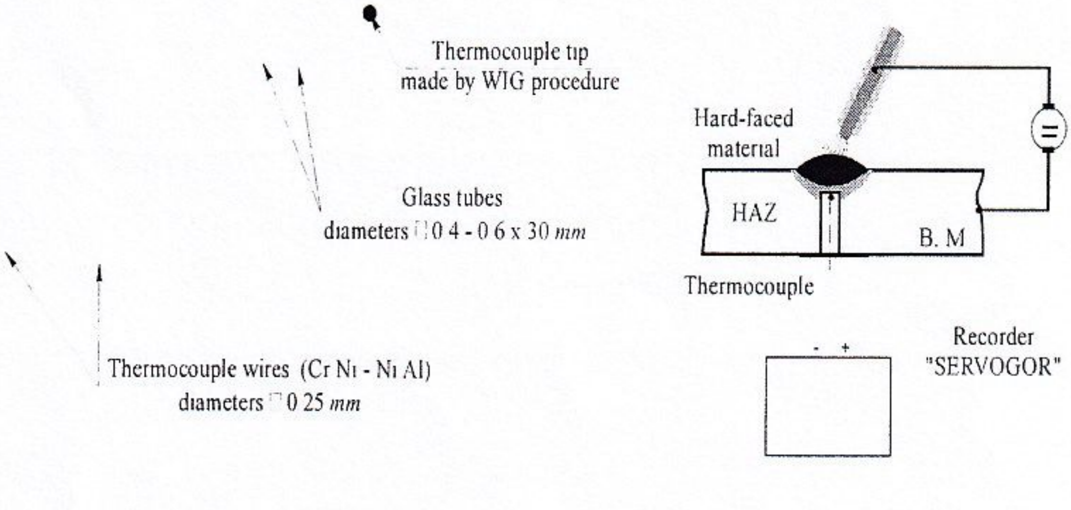


Fig. 3. Scheme of the temperature measurement

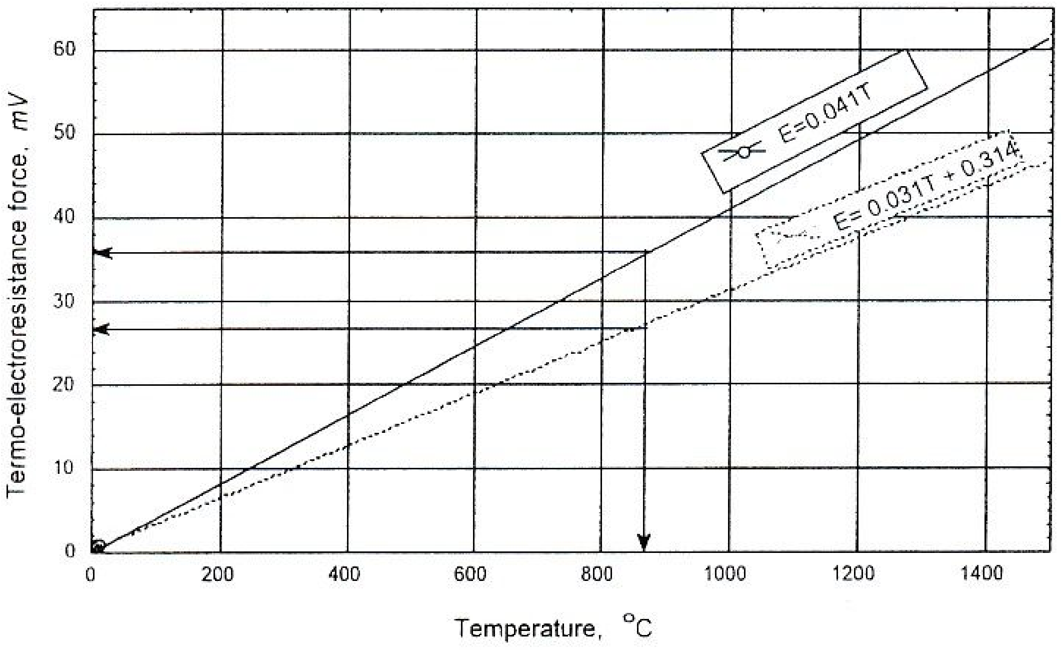


Fig. 4. Characteristics (E-T) of the used thermocouples

Tab. 5

Comparative values of the cooling time $t_{8/5}$ (s = 7.4 mm, I = 115 A, U = 25 V, q_{ef} = 2300 W) [4]

Hard facing rate, v_z, cm/s	Hard facing driving energy, q_b, J/cm	Preheating temperature, T_0/T_p, °C	Cooling time, $t_{8/5}$, s				Point/ layer
			$(t_{8/5})^J$	$(t_{8/5})^{Sgr}$	$(t_{8/5})^{EXP}$	$(t_{8/5})^R$	
0.238	9663	20	8.62	24.00	14.50	16.5-20	1/1
0.220	10560	20	9.85	29.10	17.00	20-21	24/1
0.186	12192	20	13.34	43.63	16.00	24-26	21/1
0.241	9543	70	10.14	31.17	16.50	20.5-23.5	21/2
0.172	13372	273	44.20	273.9	28.00	88-90	17/1
0.169	13609	280	47.35	304.50	34.00	94-98	10/1
0.136	16911	185	39.00	206	23.50	70-76	9/1
0.208	11058	180	20.1	84.9	27.00	42-50	18/1
0.175	13142	240	35.50	194.2	30.50	71-78	18/2
0.190	12105	178	22.80	100.3	23.00	48-54	11/1
0.183	12568	178	24.05	107.3	19.00	48.5-57	19/1
0.215	10698	169	18.19	73.4	19.50	36-43	3/1
0.150	15333	180	32.90	163.2	24.50	59-68	2/1
0.158	14557	290	55.80	386.7	31.00	104-113	2/2

Tab. 6

Comparative values of the cooling time $t_{8/5}$ (s = 29 mm, I = 190 A, U = 28 V, q_{ef} = 4256 W) [4]

Hard facing rate, v_z, cm/s	Hard facing driving energy, q_b, J/cm	Preheating temperature, T_0/T_p, °C	Cooling time, $t_{8/5}$, s				Point/ layer
			$(t_{8/5})^J$	$(t_{8/5})^{Sgr}$	$(t_{8/5})^{EXP}$	$(t_{8/5})^R$	
0.148	28757	20	11.20	14.10	16.0	10.8-12.5	2/1
0.130	32738	355	76.17	287.50	78.0	70.5-74.5	16/1
0.161	26436	231	24.36	47.30	25.0	24.27	14/1
0.152	28049	218	24.80	47.80	22.0	23.2-25.5	7/1
0.142	29870	231	29.30	60.40	24.0	27-29.6	7/2
0.258	16500	204	10.43	14.89	12.0	13.5-14.5	6/1
0.257	16912	204	10.83	15.52	12.0	13.6-14.7	6/2
0.167	25414	178	17.60	28.80	16.0	18-20	13/1
0.185	23000	235	20.20	37.10	20.5	21-23.5	21/1

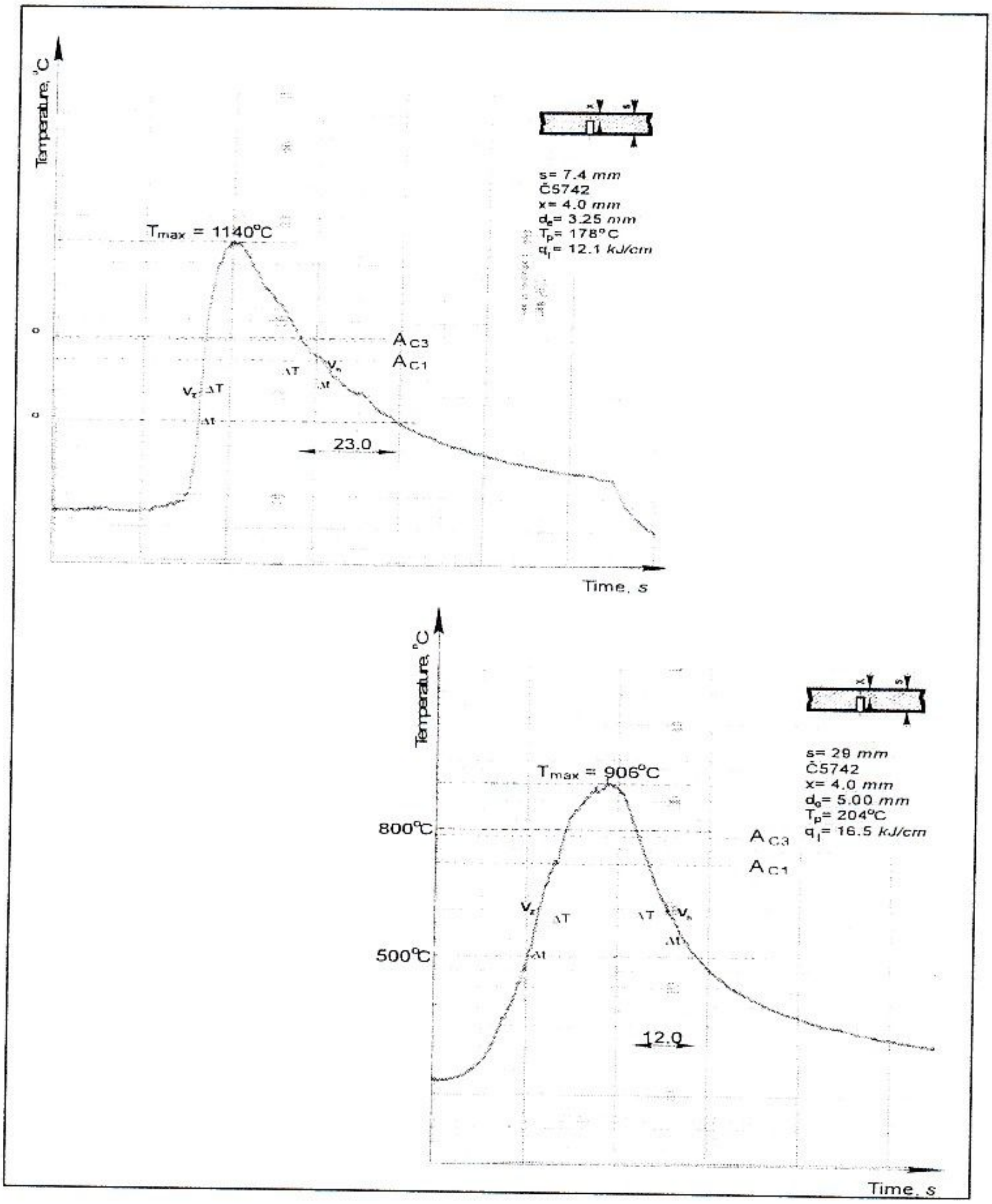
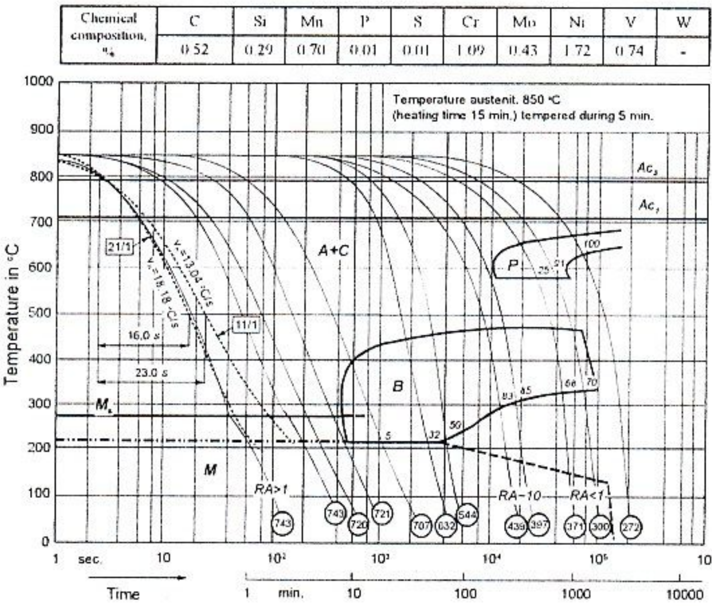


Fig. 5. TTT diagram for Č5742 [4]



Chemical composition, %	C	Si	Mn	P	S	Cr	Mo	Ni	V	W
	0.52	0.29	0.70	0.01	0.01	1.09	0.43	1.72	0.74	-

Fig. 6. Characteristics (E-T) of the used thermocouples [4, 11]

5. Relation between the input and output characteristics by TTT diagrams

By entering the cooling times $t_{8/5}$ into the TTT diagrams (Fig. 6) for the given steel, the newly created structure and hardness of the HAZ are estimated [4]. Based on known cooling curves of some characteristic temperature cycles we compared structures that are red off the TTT diagrams and those obtained by metallographic investigations [4]. The limiting cooling time $t_{8/5} = t_{100} \approx 500$ *s*, with preheating ($T_p = 300°C$), could be reached with $q_l = 60$ *kJ/cm* for s = 7.4 *mm*, namely $q_l = 150$ *kJ/cm* for s = 29 *mm*. These values of energy can not be realized by AW procedure, what means that regardless of the input hard facing parameters (q_l and T_p), the martensite-carbide structure will be obtained of the HAZ, with hardness between 721 and 743 HV. The significant correlation is noticed of the input and output characteristics, and certain deviations come from the inevitable differences in conditions of experiments realization and obtaining the TTT diagrams. The obtained results show that in order to increase plasticity, decrease hardness and residual stresses, the high relaxation of the hard faced parts must be conducted, at temperature that usually surpasses the working temperature [4, 11 - The "Ravne" steel-mill].

6. Conclusion

Based on experimental results, it was established that the cooling time in the critical interval of temperatures could be the most accurately determined by the Japanese authors' formula. Also, we proved that application of that empirical formula allows for sufficiently accurate determination of the $t_{8/5}$ time, which is the basis for choosing the optimal parameters of the hard facing regime.

The aim of this work was to point to how to, sufficiently accurately, determine the cooling rate, without repeating the expensive experimental procedure. Sufficiently accurately determined cooling rate enables reading off the structure and hardness of the HAZ directly from the TTT diagrams.

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