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INFLUENCE OF FLAME HEATING PARAMETERS ON THE HARDNESS OF HARDENED C45 STEEL

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Abstract

In this article, the impact of selected parameters of heating using a gas torch on the hardness of hardened alloy steels C45 was presented. The staff of the ship's engine room sometimes uses flame hardening during casual repairs of the machines weared as a result of operational extortions. The purpose of emergency repairs is to restore the possibility of work of ship machinery and equipment for the duration of the vessel's journey. An acetylene-oxygen torch was used to heat the steel. As the analysed parameters of the technological process, the heating time and the distance between the nozzle and the workpiece were selected. The values of the mentioned parameters have been selected so that the temperature of hardened steel is in the range from 800 to 1250 ^{o}C. The following values of the adopted machining parameters were used: the heating time was 60, 85 and 110 seconds, while the distance of the torch nozzle was 10, 20 and 30 mm. After heating, the samples were cooled by immersing in water. The research was based on a randomized orthogonal experiment plan. The purpose of the quantitative assessment of the influence of heating parameters on the hardness of hardened C45 steel, done statistical analysis variance analysis, multiple regression and mathematical optimization by the Tagichi method. Conducted tests and statistical analysis showed a significant effect of selected parameters of flame heating on the hardness of hardened C45 steel. The greatest influence on the hardness of the steel is the distance between the nozzle and the workpiece. The highest value of hardness was obtained using the following parameters of flame hardening: nozzle distance – 30 mm, heating time – 60 seconds.

Keywords: *hardening, flame heating, multiple regression, mathematical optimization, Taguchi method*

1. Introduction

At sea, vessels as a result of wear processes sometimes, crashes machine parts working during the trip. This is sometimes connected with the need to carry out temporary repair of the machine and equipment by the ship's crew, which may involve the need to produce or regenerate a damaged part (e.g. a shaft). The change in the properties of the construction material can be achieved by heat treatment. However, a ship's mechanical workshop is usually not equipped with heat treatment furnaces. Therefore, in special cases, a heat treatment can be performed during a volumetric or surface heat treatment using Oxy-acetylene welding torches or TIG arc welding equipment. Heating the material to be treated with hardening using an internal or external electric arc is a process characterized by low efficiency. The practical use of this method is limited to small-sized objects or for local hardening [2, 7, 8].

Flame heating is most often used for hardening of large-sized objects, e.g. gears, running wheels, metallurgical rollers. Austenitizing temperature and thickness of the hardened layer can be controlled by varying the relative speed of the burner and the surface of the preheated, the heating time and the distance of the torch from the workpiece surface. The conditions for flame heating are determined experimentally [1, 3-6]

This article presents the results of quantitative, statistical assessment of the impact of two parameters of the technological process of flame heating (the distance of the burner and the time of heating) on the hardness of hardened non-alloy C45 steel.

2. Research methodology

Tempering treatment of the sample was made of non-alloy steel C45 in the shape of a cylinder with dimensions of Φ30 mm x 10 mm. A welding gas torch was used to heat samples. Technological gases were used: oxygen with a working pressure of 0.35 MPa and acetylene at a working pressure of 0.05 MPa. As variable parameters of the technological process, the heating time and the distance between the nozzle of the gas burner and the workpiece were selected. During the tests, three distances of the burner were used from the heated object, namely: 10, 20 and 30 mm. The heating time of the samples was determined experimentally. As the shortest heating time, the time taken to heat the sample heated from a distance of 10 m to 800°C was assumed. The longest time was determined by specifying the time needed to heat the sample from ambient temperature to the temperature of 1250^{o}C with a burner distant from the object by 30 mm. After heating the samples for a definite time, they were cooled by immersion in water at 20^{o}C.

Tab. 1. Comparison of influence of emissions of different types of transport

Experiment number	Independent variables	
	Heating time, t [s]	**Distance from the nozzle, l [mm]**
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

where numbers 1,2,3 are codes for independent variables that take the following values:
- for the independent variable heating time (t): 1 – 60 s, 2 – 85 s, 3 – 110 s,
- for the independent variable distance from the nozzle (l): 1 – 10 mm, 2 – 20 mm, 3 – 30 mm.

The assessment of the impact of selected parameters of the flame heating for hardening was based on the measurement of hardness. The hardness of the tempered material was measured by the Vickers method. A 50 N load was applied.

To assess the effect of flame heating parameters on the hardness of hardened C45 steel, a randomized orthogonal experiment plan was used, taking into account two trivalent independent variables (Tab. 1). The plan of the experiment includes the implementation of nine trials with five repetitions.

Quantitative analysis of variance and multiple regression was used to quantify the effect of selected independent variables on surface hardness of samples. The choice of optimal parameters of heating flame by using mathematical optimization Taguchi's method was made. The optimization of flame heating parameters was carried out for the purpose "the bigger the better" by setting the parameters of the technological process in order to obtain the largest value of the S / N ratio (ETA) calculated from the formula:

$$ETA = -10 \cdot \log 1\left(\frac{1}{N} \cdot \sum_{i=1}^{n} \frac{1}{y_i^2}\right), \quad \text{for} \quad i = 1,2,...5, \tag{1}$$

where:

N – number of measurements for a specific experiment number (for the case considered N = 5),

y_i – measured trait (hardness) for "i" repeating the experiment.

3. Results and discussion

After flame heating, the average hardness values of the steel samples ranged from 428 HV5 to 694 HV5 (Fig. 1). All samples were hardened. A relationship between independent variables and the dependent variable under consideration was found. In the studied range of variability of independent variables, there is almost a full correlation between heating time (r = -0.93) and nozzle distance (r = 0.95) and hardness of flame-hardened C45 steel. The heating time is inversely proportional to the surface hardness of the flame-heated C45 steel.

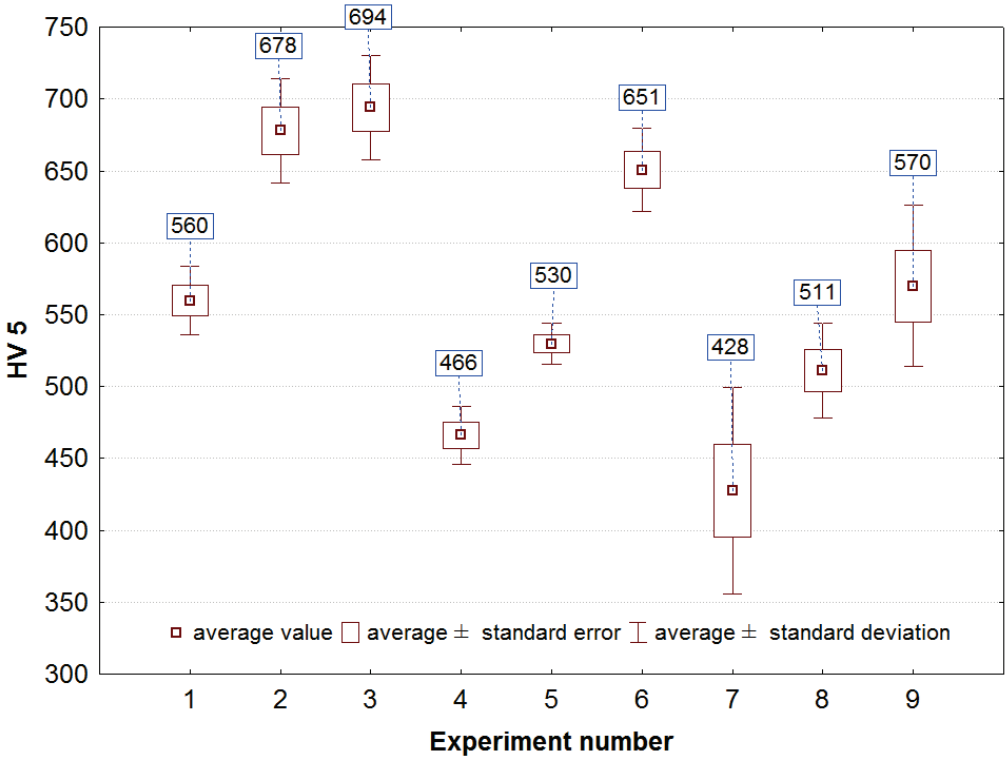

Fig. 1. The results of basic statistical analysis of the hardness measurement results of the test specimens after flame hardening

a) *b)*

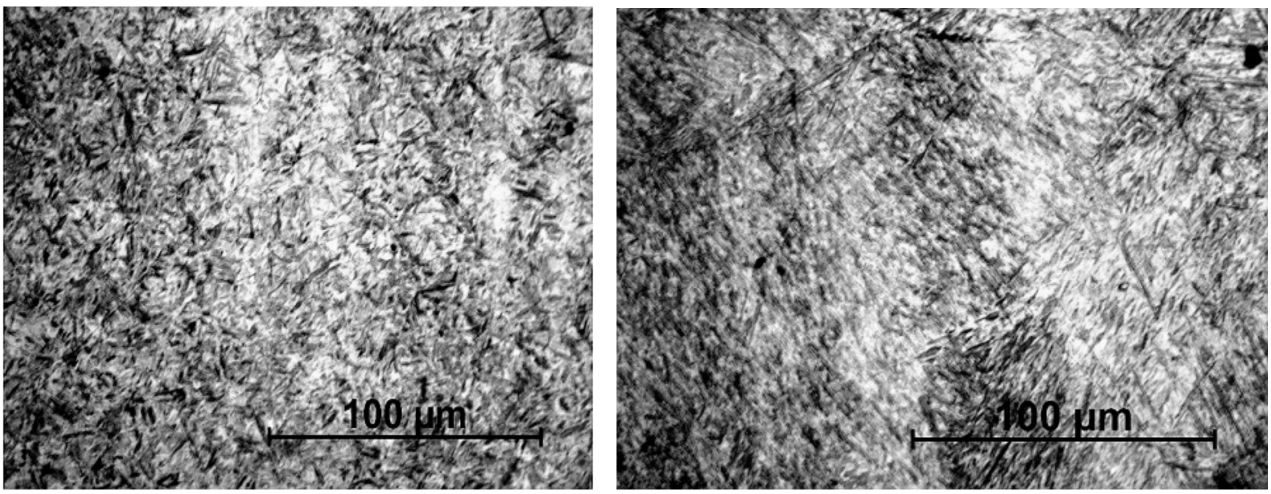

Fig. 2. Sample microstructures of C45 steel samples that were flame-hardened using heat treatment parameters: a) t = 60 s; l = 30 mm (HV 5 = 694), b) t = 85 s, l= 10 mm (HV 5 = 428)

Tab. 2. Sheet of analysis results for variance of dependent variable (steel hardness)

	SS, sum of squares	**F(2,6), test result**	**p, calculated level of significance**
Regression result	74486.67	44.88	$2.5 \cdot 10^{-5}$
Residual components	4979.33	-	-
Sum	79466	-	-

Tab. 3. Results of multiple regression analysis for results of the hardness measurements of hardened C45 steel ($F(2,6) = 44.88$ $p < 2.5 \cdot 10^{-5}$, $R = 0.97$, $R^2 = 0.94$, standard error of estimation = 28.81)

	BETA	**B**	**t**	**p**
Y Intercept		654.07	13.81	0.000009
Heating time, t [s]	-0.65	-2.97	-6.32	0.000733
Distance of the nozzle, l [mm]	0.72	8.3	7.06	0.000405

where:
F(2,6) – result of the analysis of variance,
R – multiple correlation coefficient,
R^2 – multiple correlation coefficient,
BETA – standardized multiple regression coefficient,
B – multiple regression coefficient,
t – the student's t-test result,
p – calculated significance level for the Student's t-test result.

Metallographic examinations showed the presence of martensite in all analysed samples (Fig. 2). It was found that the applied flame hardening parameters influence the size of the martensite grains. The smallest martensite grains were observed for samples heated with the following parameters: t = 60 s, l = 30 mm. The austenitizing temperature was then around 800°C. However, the largest martensite grains were obtained using the following parameters: t = 110 s, l = 10 mm. The austenitizing temperature was then around 1250°C.

The obtained results of the variance analysis of the dependent variable (Tab. 2) allow to state that both adopted parameters of flame heating statistically significantly affect the hardness of C45 steel. Only 6% (4979.33/79466) sum of the squares of the variance of the dependent variable (steel hardness) is not explained by the influence of the heating time and distance of the torch nozzle from the sample.

Table 3 presents the results of multiple regression analysis for the quantitative assessment of the effect of heating parameters on steel hardness. The value of the multiple correlation coefficient R = 0.97 indicates a very high correlation between the adopted input variables and the dependent variable. Considering the values of standardized multiple regression coefficients, it can be concluded that the distance of the gas torch nozzle from the workpiece (BETA = 0.72) exerts a greater influence on the hardening hardness of the steel than the heating time (BETA = -0.65). At the assumed level of significance $\alpha = 0.05$ one can infer about the statistical significance of the calculated values of multiple regression coefficients. Thus, the adopted input variables and their values have a significant influence on the value of the parameter being evaluated. This is evidenced by the results of the Student's t test. The prediction of the hardness of the flame-hardened C45 steel can be made by the equation (2) of the multiple regression. The large value of the coefficient of determination ($R^2 = 0.94$) indicates a very good fit a statistical model to the measurement results. Fig. 3 shows the relationship between hardness values (HV5) determined from equation (2) with observed values.

$$HV5 = 654.1 - 2.97t + 8.31l \pm 28.81, \tag{2}$$

where:

t – heating time, s,
l – distance from the nozzle, mm.

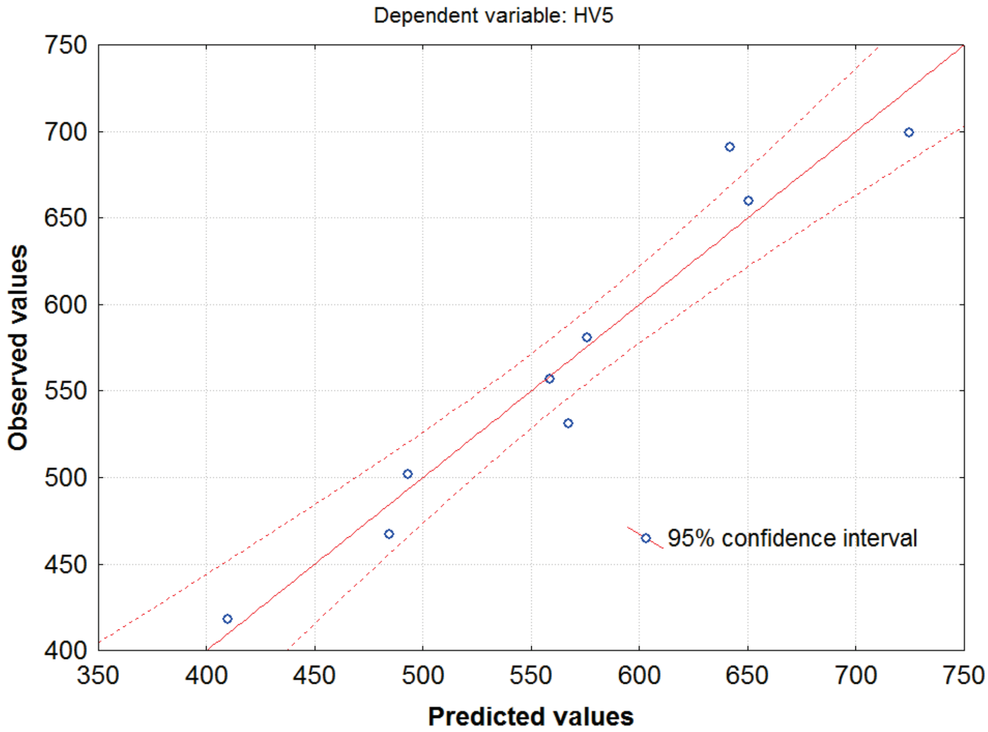

Fig. 3. Graph of dependencies between predicted values (calculated from equation (2)) and observed values

Tab. 4. Values of calculated ETA coefficients from equation (1) for each point of the experiment plan (Tab.1)

Experiment number	**Heating time, t [s]**	**Distance from the nozzle, l [mm]**	**ETA [-]**
1	60	10	54.94
2	60	20	56.59
3	60	30	56,80
4	85	10	53.35
5	85	20	54.47
6	85	30	56.24
7	110	10	52.34
8	110	20	54.13
9	110	30	55.00

The optimization of flame heating parameters of C45 steel was carried out using the Taguchi method for the purpose “the bigger the better”, based on such determination of technological process parameters for which the highest value of S/N ratio (ETA) calculated from formula (1) was obtained. Tab. 4 presents the values of the ETA coefficient for individual measurements made according to the planned experiment. The largest value of the ratio of the signal ratio (S) to noise (N) was obtained for measurements from the layout number 3 of the experiment plan. The value of this coefficient was 56.8. Based on the theory developed by Taguchi, the maximum value of the ETA index is sought. Based on the average values of the ETA coefficient, it can be concluded that the maximum value of this coefficient has the maximum material heating time equal to 60 s. In turn, the optimal distance of the nozzle from the workpiece, taking into account the influence on the input variable of non-measurable disturbing factors, is l = 30 mm. Fig. 4 presents the average values of ETA coefficients for the assumed values of independent variables. On the basis of the graph (Fig. 4) it can be confirmed, the value in the ETA coefficient (and thus the hardness of hardened steel) increases with the increasing distance of the torch nozzle from the workpiece and the decreasing heating time.

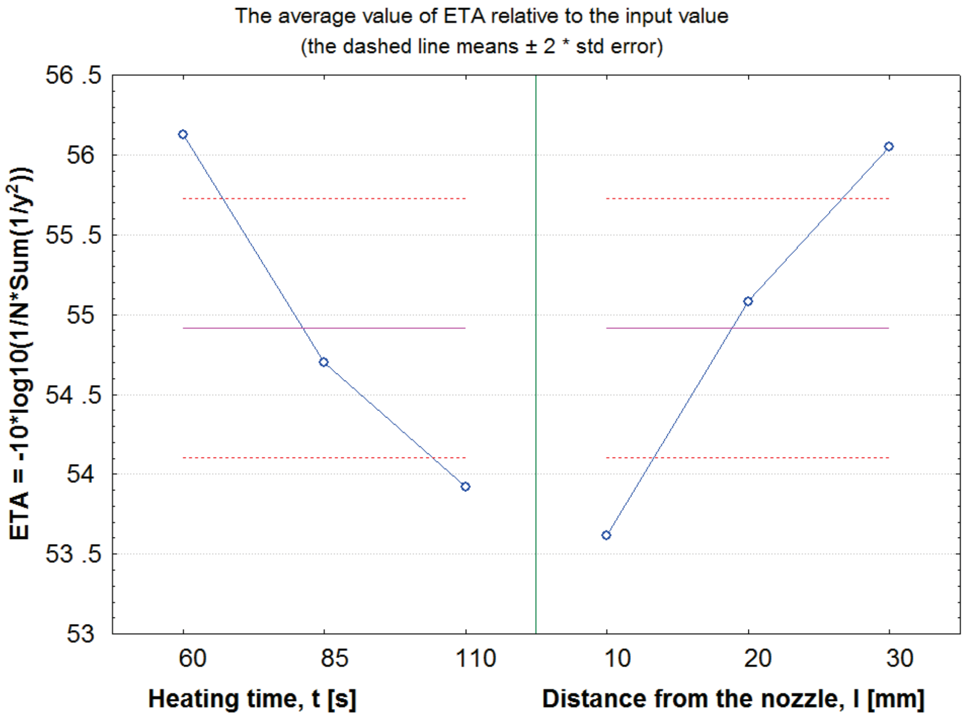

Fig. 4. Graph of average values of ETA coefficient for adopted values of independent variables

Tab. 5. Results of hardness prediction of C45 steel after flame hardening under optimal conditions (l = 30 mm, t = 60 s)

Variable	Weight, B	Value	B*value
Heating time, t [s]	-2.97	60	-178.4
Distance from the nozzle, l [mm]	8.3	30	249
Y Intercept	-	-	654.07
Predicted value, P	-	-	724.67
P - confidence interval	-	-	677.67
P - confidence interval	-	-	771.66

Table 5 presents the prediction results of hardness of flame-hardened steel for optimal conditions. With 95%, probability it can be concluded that machine parts made of C45 steel, after flame hardening, should have hardness ranging from 678 to 772 HV5.

4. Conclusions

1. In the mechanical workshop of a marine power plant, flame heating can be used for heat treatment of regenerated and machined parts of machines.
2. During flame hardening, in the absence of temperature measuring instruments use such parameters of the technological process as heating time, distance of the gas burner nozzle from the workpiece.
3. However, one should remember about the temperature control of austenitizing-tempered material, even in a subjective way.
4. The conducted tests and subsequent statistical analysis showed that the assumed values of both flame-heating parameters (heating time, distance from the nozzles) have a significant statistical effect on the hardness of hardened C45 steel.
5. The largest of the considered independent variables, the hardness of hardened C45 steel was affected by the distance of the workpiece from the nozzle of the burner.

6. The highest hardness (694 HV5) of flame-hardened C45 steel was obtained using the following parameters: distance from the nozzle - l = 30 mm, heating time - t = 60 s.
7. Using the multiple regression equation (2), it is possible to calculate, at the significance level α=0.05, that the hardness of hardened steel in optimal conditions (l = 30 mm, t = 60 s) should be in the range from 678 HV5 to 772 HV5.

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