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CONTROL FACTORS ON THE HEAT TREATMENT PROCESS APPLIED TO A537 STEEL FOR INCREASING HARDNESS USING HARDENING AND TEMPERING

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ABSTRACT

The paper is based on laboratory experiments of heat treatments applied to samples of A537/A537M steel. The work continues other previous works aimed at modifying structures and properties of this steel, including through surface treatments. The experiments were performed using Taguchi methods from Quality Engineering. A number of four factors were selected as influencing the structure after heat treatment: heating temperature for hardening, cooling rate on hardening, time and tempering temperature. A number of nine experiments were performed using an L9 orthogonal matrix. Objective function was changed to maximum hardness after the heat treatment regime. The results show that the tempering temperature has the greatest influence on the final hardness of the A537 steel samples.

KEYWORDS: HSLA, A537/A537M, heat treatment, Taguchi methods, quality engineering

1. Introduction

The A537 steel is part of the HSLA steel group, which means that in accordance with the specifications of use, significant reductions in the mass of the finished assemblies can be obtained. The chemical composition of the steel (Table 1) leads to an equivalent carbon that allows heat treatment by hardening and tempering but also allows diffusion welding.

The A537 steel (Table 2), [1] is a *C-Mn-Si* (carbon-manganese-silicon) steel being produced in the form of thick sheet in three classes having thicknesses covering the applications: under 65 mm, between 65 mm and 100 mm and over 100 mm. In Table 2 is showing that for the same chemical composition of steel the beneficiary can choose for three classes of product depending on the heat treatment. This means that parts can be made from sheet metal that can be treated individually to obtain the most convenient complex of properties. Classes 2 and 3 can be delivered in the form of table sheets treated entirely in section by specialized installations. This form of delivery offers the most convenient price ratio per kg of product.

Table 1. *ASTM A357/357M chemical compositions* [1]

element	thickness	heat analysis	product analysis
m.u.	mm	mass %	mass %
carbon		0,24	0,24
manganese	<40	0,70… …1,35	0,64… …1,46
	>40	1,00… …1,60	0,92… …1,72
phosphorus	-	max.0,035	
sulphur	-	max.0,035	
silicon	-	0,15… …0,50	0,13… …0,55
copper	-	max.0,35	max.0,38
nickel	-	max.0,25	max.0,28
chromium	-	max.0,25	max.0,29
molybdenum	-	max.0,08	max.0,09

The properties are dependent on the class of manufacture, the thickness and the heat treatment applied (Table 3), respectively.

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The work continues the concerns for the optimization of the properties of A537 steel through experiments of heat treatments performed in laboratory conditions using the TM procedure from Quality Engineering. Compared to previous works, the type of objective function has changed, which has led to its own results in accordance with the literature [1].

An example is the use of this steel, which requires as much hardness as possible, when making wear parts for agricultural machines.

Table 2. *ASTM A537/537M mechanical properties in function of heat treatment* [1]

class	heat treatment	thickness	yield strength	tensile strength
u.m.	-	mm	Mpa	Mpa
1	normalized	under 65	345	485
		over 65	310	450
2	quenched and tempered	<65	415	550
		65...100	380	515
		over 100	315	485
3	quenched and tempered	under 65	380	550
		65...100	345	515
		over 100	275	485

Table 3. *Mechanical and plasticity properties in function of A537 class and thickness* [1]

properties	thickness	class 1	class 2	class 3
m.u.	mm	MPa	MPa	MPa
tensile strength	<65	485...620	550...690	550...690
	65..100	450...585	515...655	515...655
	100...150	...	485...620	485...620
yield strength	<65	345	415	380
	65..100	310	380	345
	100...150	...	315	275
Elongation in 50mm,%	50			
	<100	22	22	22
	>100	...	20	20
Elongation in 200mm,%		18	...	...

Notations:

n - target function;

i - number of experiment. i = 1…9.

Abbreviations:

HSLA - High Strength Low Alloy;
TG - Taguchi methods;
OA - Orthogonal Array;
ANOVA - Analysis of Variance;
HV - Hardness Vickers.

2 Experimental conditions

For the heat treatment experiments, samples of A537 / 537M sheet steel, with a thickness of 12.7 mm (1/2 inch), were used, for which the mentioned thickness is the characteristic dimension for heat regimes, similar to the treatment processes in factory section. The equipment used: electric heat treatment furnace with a working surface of 450 cm^2 and a maximum working temperature of 1200 °C and with thermal regimes controlled with ARE612 [2, 3]. Each of the hardening baths has 15 litres of liquid (water, stream of water, oil). The influencing factors that are considered for the given conditions of the experiment, are shown in Table 4, with the specification of some domains of variation.

The factors for the steel with hardening and tempering treatment in Table 5 were selected on the basis of the steel standard [1] and specialist literature [4, 5]. The same table shows the levels that are set for each factor (Table 5).

The L9 typed orthogonal matrix is shown in Table 6. It determines an experiment matrix with 9 lines (partially factorial experiments) and replaces a matrix with 34 with 81 lines (specific to full factorial experiments). The main mathematical properties of orthogonal matrices are related to the constant occurrence frequency of each level of each factor which ultimately leads to a mechanism for simplifying the calculation of specific errors [6-8].
The beneficial effect of reducing the number of experiments is useful only if the mathematical model of the experiment (TM, Taguchi Methods) and the mathematical model for interpretation of the results are followed. The reduction of the number of experiments and the related costs is found in the statistical approximation of the objective function of the optimal value and not in finding it as in the case of total factorial methods.

Table 7 shows the experiment matrix used to see the influence of four factors from quenching and tempering conditions on the final hardness of the samples.

Peculiar to this experiment matrix is that the lines that specify the conditions of each experiment differ greatly in their sequence. This also shows one of the difficulties of using orthogonal experiment matrices:

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- First: namely the variation of the experiment conditions. Achieving the required conditions is a condition for obtaining viable results.
- A second important difficulty is that if an experiment fails it must be resumed under the required conditions.

3. Results and discussions

After performing all nine complete experiments (with hardening and tempering), the samples were subjected to the Vickers surface hardness test. Three measurements (HV5, 5 kgf) were performed on each sample in central areas to eliminate the edge effect, and the result of the average hardness on each of the nine samples is shown in Table 8.

According to the initial model, it is considered a favourable dependence, when the hardness has maximum value. Taguchi recommends a "the biggest is the better" function [6, 8]. The objective function has in this case the equation:

$$n_i = 10\,log\,HV_i$$

Where: n is target function for i experiment line, and HV_i is the measured hardness for i sample [6], where $i = 1 \ldots 9$.

The values of target function for all the nine experiments are shown in Table 9.

Specific TM is the construction of the average effect of each level of each factor on the whole set of experiments, by mediating the objective functions in which the level of a considered factor participates.

The calculus relations and results are centralized in Table 10 and then represented graphically in Fig. 1. These observations are found in the heat treatment regime recommended by the procedure based on the highest value of each factor level effect.

Table 4. *Factors that are considered to influence the experiment*

No.	Factors	u.m.	values domain
1	chemical compositin of steel	%	
2	temperature for quenching	°C	800..950
3	cooling speed for quenching	°C/s	0…2
4	tempering temperature	°C	620…690
5	tempering time	h	1hour/1inch thickness
6	non-uniformity of temperature in the treatment furnace	%	+/- 5%
7	chemical compozition of furnace atmosphere	%	
8	samples thickness	mm	1/2inch

Table 5. *Selected factors for A537 heat treatments experiments*

Symbol	Factors	um.	levels		
			1	2	3
A	temperature for quenching	°C	880	900	920
B	tempering temperature	°C	640	660	680
C	tempering time	h	0.5	1	1.5
D	cooling speed for quenching	°C/s	flow water	water	oil

Table 6. *L9 standardized orthogonal array* [6, 7]

experiment	factori			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 7. *Experimental matrix with specified values of factors*

experiment	Specified factors			
	A	B	C	D
u.m.	°C	°C	h	grd.
1	880	640	0.5	flow water
2	880	660	1	water
3	880	680	1.5	oil
4	900	640	1	oil
5	900	660	1.5	flow water
6	900	680	0.5	water
7	920	640	1.5	water
8	920	660	0.5	oil
9	920	680	1	flow water

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Table 8. *Final hardness for each experiment and target function*

experiment	HVm	Target function
m.u.	daN/mm2	dB
1	317	25.01
2	303	24.81
3	289	24.61
4	315	24.98
5	286	24.56
6	305	24.84
7	330.5	25.19
8	294.5	24.69
9	309.5	24.91

Table 9. *The average effect of each level of each factor*

the average effect of each level	relation	value, dB
m_{A1}=	$1/3(n_1+n_2+n_3)$=	24.81
m_{A2}=	$1/3(n_4+n_5+n_6)$=	24.80
m_{A3}=	$1/3(n_7+n_8+n_9)$=	24.93
m_{B1}=	$1/3(n_1+n_4+n_7)$=	25.06
m_{B2}=	$1/3(n_2+n_5+n_8)$=	24.69
m_{B3}=	$1/3(n_3+n_6+n_9)$=	24.79
m_{C1}=	$1/3(n_1+n_6+n_8)$=	24.85
m_{C2}=	$1/3(n_2+n_4+n_9)$=	24.90
m_{C3}=	$1/3(n_3+n_5+n_7)$=	24.79
m_{D1}=	$1/3(n_1+n_5+n_9)$=	24.83
m_{D2}=	$1/3(n_2+n_6+n_7)$=	24.95
m_{D3}=	$1/3(n_3+n_4+n_8)$=	24.76
	media=	24.85

Table 10. *The average effect of the level of each factor*

	Factor	Levels			
		m.u.	1	2	3
A	temperature for quenching	dB	24.811	24.80	**24.93**
B	tempering temperature	dB	**25.062**	24.69	24.79
C	tempering time	dB	24.848	**24.90**	24.79
D	cooling speed for quenching	dB	24.827	**24.95**	24.76
				m	24.85

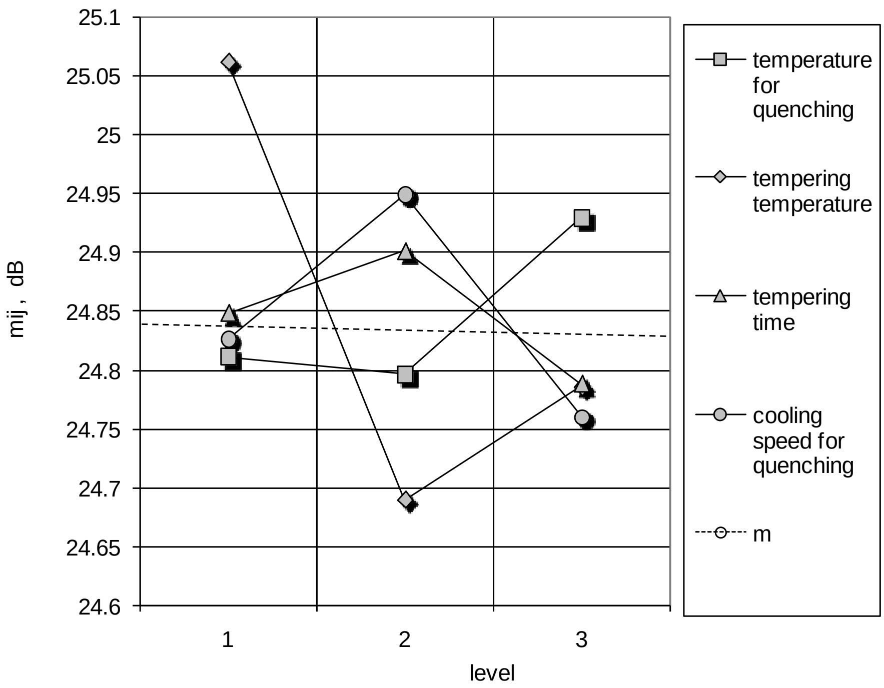

Fig. 1. *Graphical representation of the average effect of the level of each factor*

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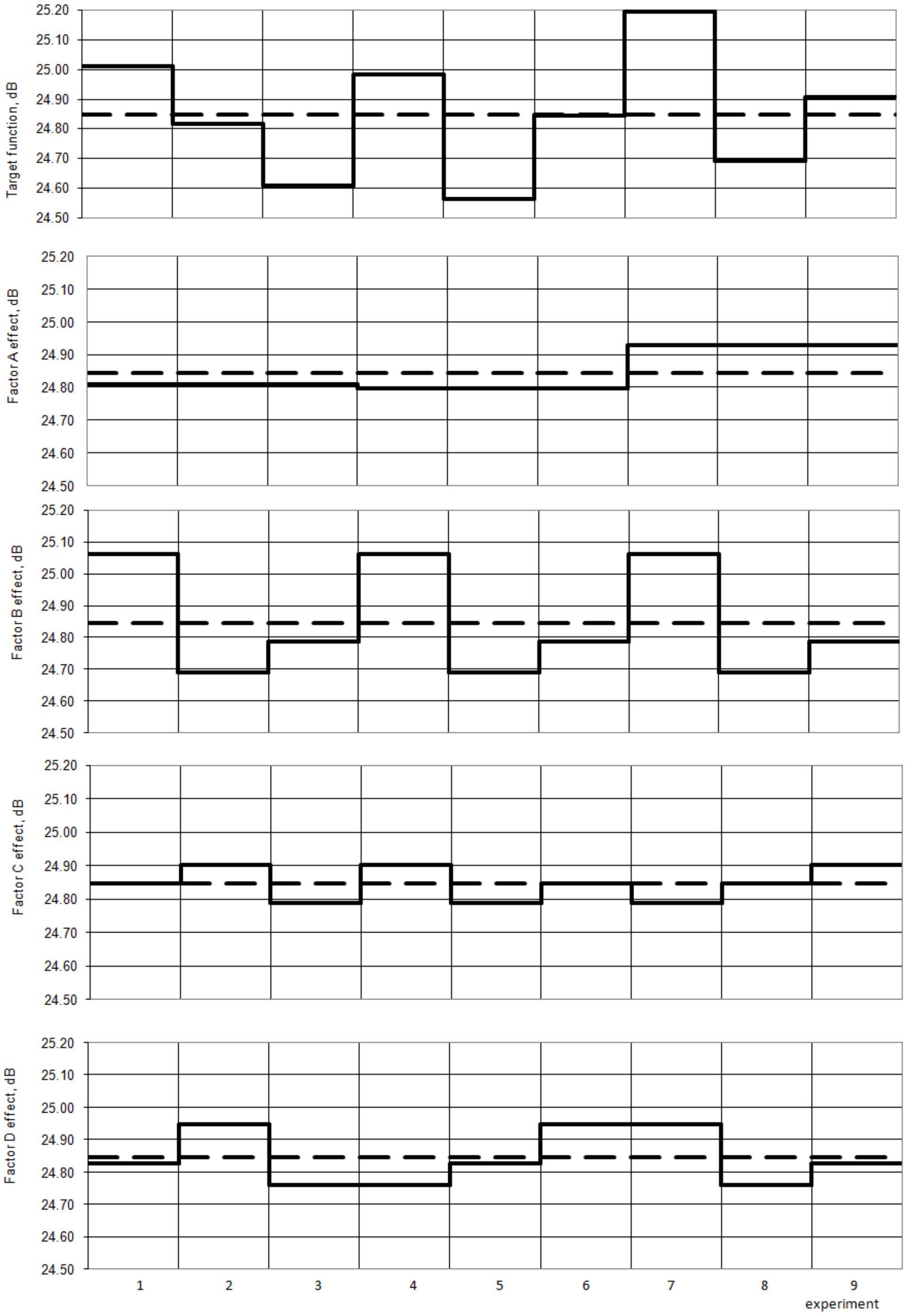

Fig. 2. *Graphical representation of the objective function with the number of the experiment and the additivity of the effect of factors A, B C and D*

4. Conclusions

Regarding the influence of the average effect of each level of the factors considered, the following can be observed:

- Heating temperature for hardening with higher value leads to increased final hardness.
- The lowest tempering temperature leads to the highest hardness.
- Cooling for hardening greatly influences the hardness, water cooling being the best solution.
- The firing time of 1h leads to a maximum hardness.

The additivity property is observed in Fig. 2. By summing the deviation from the mean of factors A, B,

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C and D for each experiment and leading to the objective function for that experiment. The procedure is inspired by FFT [6].

The main mathematical properties of orthogonal matrices are related to the constant occurrence frequency of each factor level which ultimately leads to a mechanism for simplifying the calculation of specific errors.

Regarding Fig. 3, which shows the influence of the factors on the experiments performed, it can be seen that the factor B (return temperature has the most important influence (almost 70%) which corresponds to the practical experience that the return temperature by thermal activation of processes determines the final mechanical properties. The second important factor is the cooling rate on hardening (drasticity of the cooling medium). Factors B and D cumulatively determine a weight of 84.5% and can be considered the control factors of the heat treatment process (hardening + tempering).

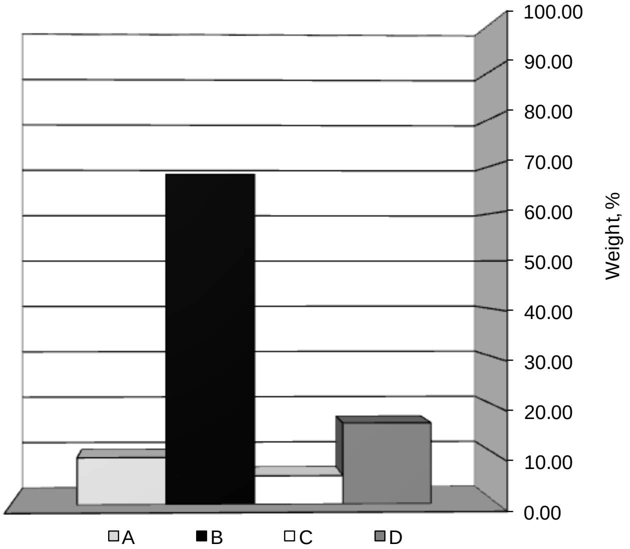

Fig. 3. *Weight factors influence on experiments*

Factors A and C accumulated an influence of approx. 15.5% and can be considered environmental factors. Technological experience shows that lower weight technological factors can be considered.

From a technological point of view, the weight of the factors practically determines the degree of precision with which the adjustments (settings) are made. If 2.5% accuracies are usually used, settings with 0.5% accuracy are made for the mentioned control factors, and max.1%. The procedure allows to reduce the variability of the finished products, the heat treatment technology applied to A537 steel being based on repeatability. The recommended optimal regime: A3B1C2D2 [6-8].

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