Obtaining the optimal parameters in a laser hardening process through Taguchi method

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This paper presents an application of Taguchi method for finding the optimum combination levels of parameters that influence a laser hardening process. There were envisaged three types of laser parameters: laser power P, spot diameter d, and scan speed v, and their influence on the maximum microhardness and depth of hardening obtained during the laser hardening process. The Taguchi method is a powerful tool in quality management because it can offer the optimal parameter combination even in the absence of an experiment procedure that uses those levels, and so it is not necessary to make too many experiments in order to obtain the optimal setting. It is only necessary to make those that use certain combinations of parameters. The ANOVA technique was used to identify the most important processing parameters during this process. The results point out the most significant parameter among those considered in this paper, for each studied case, first, for the case when only a higher microhardness is desired, and second, for the case when a higher microhardness and a greater value for the depth of hardening are envisaged, for a C45 steel, and also offer the combination of process parameters that can be used for reaching these goals.

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1. Introduction

The paper presents a method of optimization the process parameters in laser heat treatment surface hardening of metal, to obtain a hard layer with higher mechanical properties.

In surface hardening, the metallic material is heated in the field of austenite, followed by rapid cooling (the transformation temperature is below the melting temperature). After interaction laser with metallic sample, quantum energy of photons from laser radiation is ceded to the electronic gas from the metal surface, which in turn gives energy to the crystalline grid [1].

After the action of laser radiation, the heating of the surface layer surface takes place in a time of order 10^{-9} s, and the heat accumulated in this layer is quickly dissipated by conduction in the sample. Cooling the heated zone has the effect of hardening the material in the treated area.

Surface hardenings is used when is desired a hardening only in the material surface and the base material keep the same properties.

Superficial heat treatments can be made by conventional methods, but the use of laser technology has some advantages [1,2]: high quality and precise control of dimension layer processing; processing without contact with the sample; negligible deformation of the piece after located heat treatment; selective hardening of the piece at the depth and breadth required in places with excessive wear of metal without affecting the desired properties of the substrate; surface hardening of the cavities by directing laser radiation by different focusing modes; forming the hardened lanes on the surface which made be treated toward hard layer over the entire surface, which is susceptible to crack, to deform; there are no polluting; are relatively easy to automate.

Since the heating process is very complex there are many factors that can modify the work conditions and phenomena evolution, it is necessary to establish optimal parameters setting of laser system used.

Basic parameters of laser processing of materials, which were envisaged in the herein study, are: laser power radiation (P); scanning speed (V) (piece speed in front of the laser beam), which influencing the interaction time of the laser radiation with the sample; and the diameter of laser beam radiation (d), [3, 4, 5].

The aim of this study is to determine optimal process parameter values in order to obtain, first, only higher microhardness values in the hardened layer, and afterwards to obtain best results in case when two characteristics of the sample are envisaged, namely a high microhardness and also a deeper hardened layer.

One powerful technique that can be used in order to achieve a high quality level process is Taguchi method, developed by Genichi Taguchi, and introduced in 1986, in paper [6]. He was inspired by the concept of design of experiments, concept introduced by Fisher in 1920, and by the notion of orthogonal array, which became an important instrument used by him in developing his method.

The Taguchi method represents in fact a method of quality assurance and control, used in the design stage of a production process. There exist many paper focused on applying Taguchi method for optimizing different processes. It can be use in many different domains, not only in hardening [7, 8], in laser processing [9], or other manufacturing processes [10, 11, 12], but whenever the settings of interest parameters are necessary [13, 14, 15].

After applying this technique the optimal parameters setting is deduced, in each case. The process parameters optimal values depend on the objectives formulated, because they are not the same for both cases.

In order to estimate the error variance and to rank the process parameters according to their importance a statistical tool is used, namely the analysis of variance (ANOVA). The most important process parameter is found and, like the optimal values of the parameters, it depends on the purposed objective.

2. Basic elements in applying Taguchi method

The Taguchi method represents a quality engineering method used for finding the optimal parameter setting necessary to obtain higher performance for the output characteristics, in order to have a high quality process.

The Taguchi method is in fact an optimization technique, which was initially developed to optimize a single performance characteristics, but later it was used to solve problems in which multiple responses were envisaged [7].

As any of the optimization techniques it uses objective functions in formulations. In Taguchi method the objective function is a loss function, usually a log function of desired output, named Signal –to Noise ratio (S/N ratio).

Optimization problems can be divided into two main categories from the point of view of Taguchi methods, according to their nature: static problems and dynamic problems. Static problems are those concerned with several control factors that decide the desired value of a certain characteristic, as in our cases. In case of static problem the optimization is achieved by using different types of S/N ratios, which are evaluated in different manners according to the type of problem to solve, depending on the characteristic's nature: smaller - the-better, case in which the smaller the value of the characteristic, the better the performance is; higher - the-better, when a higher value for the characteristic leads to a better performance; nominal - the - best, when only a certain value of the characteristic is needed in order to achieve the best performance.

When applying Taguchi method the evaluations are made for S/N ration instead of mean value, because it can reflect both the mean and the variation of the performance characteristics. Thus, the discussion of the results becomes easier.

Taguchi method uses the orthogonal arrays as efficient tools for obtaining a well planed set of experiments. Orthogonal arrays allow studies involving a large number of factors without too excessive costs, because their use reduces the number of experiments required. In case of using Taguchi method for parameter design, the experiment doesn't need to run under the optimum levels of parameters. That's why it is necessary to verify if their optimum levels give the expected result, after running the validation experiment, the experiment in which the involved parameters have the optimum levels.

As we earlier mentioned, this paper apply Taguchi method in order to find the optimum levels of three of the most important parameters involved in laser hardening process of C45 steel. We consider these parameters as being: the laser power (P[W]), scan speed (V[mm/s]), and laser spot diameter (d[mm]). In this study we consider that no interaction arises between the parameters

Experiments were done considering different values for each of these parameters. For the laser power three values have been envisaged, namely: 800 W, 1000 W, 1200 W. For the scanner speed there were considered three values too: 5 mm/s, 10 mm/s, 15 mm/s. Only two values were consider for the laser spot diameter: 2.4 mm and 4mm.

The values of the mentioned parameters represent the levels of the control factors in Taguchi approach. So for laser power and for the speed we have considered three levels and for the beam diameter only two. Table 1 presents the process parameters and their associated levels

Table 1. Factor levels.

Factors	Symbol	Level 1	Level 2	Level 3
Laser Power (P)	A	800	1000	1200
Scanner velocity (V)	B	5	10	15
Spot diameter (d)	C	2.4	4	-

The selection of an orthogonal array is made in concordance with the total degrees of freedom of the parameters. In this study, two of the three parameters have three levels and one has only two levels, so the total degrees of freedom for the parameters are equal to 5. The degrees of freedom for the orthogonal array should be greater than or at least equal to those for the process parameters. Because of the difference between the number of levels, a mixed level orthogonal array was considered. For case of two parameters with three levels, and one with two levels in literature orthogonal arrays are presented in paper [16, 17] We have considered in this paper a modified L9 orthogonal array, obtained from the classical L9 orthogonal array according to procedure described in [17]. Table 2 shows the considered array, 1,2,3 being the corresponding levels of parameters involved .

Table 2. L9 modified orthogonal array.

Nr. of experiment	A	B	C
1	1	1	1
2	1	2	2
3	1	3	1
4	2	1	2
5	2	2	2
6	2	3	1
7	3	1	2
8	3	2	1
9	3	3	2

Each line of this array shows the combinations of factor levels which need to be considered for the required experiments. So, 9 experiments with certain values of the mentioned parameters were run. This is the moment when we can see one of the most important reasons for which Taguchi method is considered as a very powerful technique for solving problems regarding parameter optimization: the small number of experiments to be done. For example comparing it with another well known method, the full factorial design, when 18 experiments need to be done in case of considering two parameters with 3 levels and one with two levels, we can see that the number of necessary experiments is reduced at half (see [18]). The reduction is bigger in case of more levels or in case of having much more factors.

3. Experimental procedure

Considering the three parameters combinations, suggested by the modified L9 orthogonal array, experiments were made on sample with following dimensions 35x15x5mm, made by C45 steel with chemical composition given in Table 3.

Table 3. Base material, chemical composition (weight %).

Chemical Composition %										**Microstructure**	**hardness (HV)**
C	Co	Cr	Cu	Sn	Mn	Mo	Ni	P	Si		
0,49	0,12	0,159	0,223	0,015	0,67	0,24	0,16	0,013	0,217	Ferito-pearlitic	224

For surface hardening it is used a CW CO_2 laser with 10.6 μm wavelength (Fig. 1).

Moving the sample with different speeds, in front of the laser beam, which is fixed, hardened surface lines are obtained.

Fig.1. CO_2 laser used in surface heat treatment.

To increase the absorption of laser radiation, the metallic surface was covered with a matte black paint.

After processing with laser radiation, the samples were sectioned transversely and embedded in Bakelite powder on a Buehler-Simplimet 2000 press. After embedding, the sample was polished on a Buehler-Vector machine and then attacked with nital 2% and analyzed with optical microscope Reichert UnivaR.

The microhardness measurement was performed using Vickers methods with Leco Microhardness Tester. Vickers microhardness was determinated in transversal section of the hardened sample, using a 50g as load and 10 s for penetration time.

After superficial hardening by heating with high power laser spot, followed by rapid cooling with a thermal gradient $\frac{dT}{dt}$, practically unattainable by conventional methods, steel C 45 was solidified in martensitic phase Fig. 2.

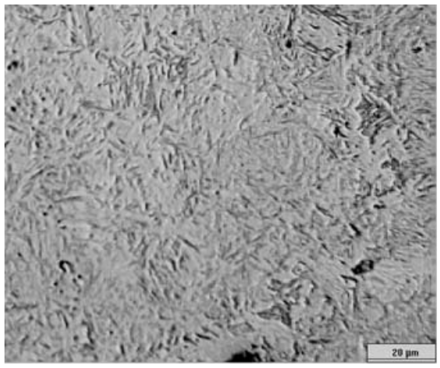

Fig. 2. Martensitic structure of hardened layer.

4. Taguchi method and ANOVA results for optimal parameter setting – case of single response (higher microhardness)

We apply the Taguchi method in order to find the optimal parameter setting in case when the objective is to obtain a C 45 steel sample with a higher microhardness. We have a static problem of higher-the-better type, for which a greater S/N ratio corresponds to a better quality. The results of the experiments are presented in Table 4, and the S/N ratio is evaluated in each case according to formula:

$$\eta_s = -10\log_{10}\left(\frac{1}{y_s^2}\right), s = \overline{1,9}$$ where y_s represents microhardness value for experience nr s.

Table 4. Experiment measured values for the C45 steel highest microhardness, under the mentioned conditions and S/N ratio.

Nr. exp	Power	Speed	Diameter	Micro hardness	S/N ratio
1	800	5	2.4	760	57.61627
2	800	10	4	830	58.38156
3	800	15	2.4	802	58.08349
4	1000	5	4	775	57.78603
5	1000	10	4	762	57.6391
6	1000	15	2.4	780	57.84189
7	1200	5	4	738	57.36113
8	1200	10	2.4	781	57.85302
9	1200	15	4	748	57.47803

We evaluate the mean values of S/N ratio for each level of the involved factors. The results are shown in Table 5 and in Fig. 3.

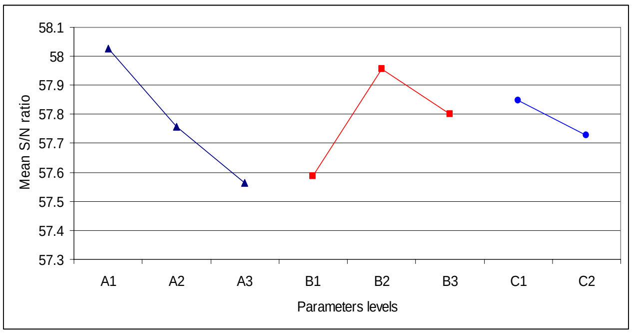

Fig. 3. Mean values of S/N ratio for parameters, according to their levels.

Table 5. S/N ratio for each level.

Symbol	Factor	Mean S/N ratio (dB)				Total mean value for S/N ratio
		Level 1	Level 2	Level 3	Max distance	
A	Power	58.02711	57.75568	57.56406	0.463047	57.78228
B	Speed	57.58781	57.95789	57.80114	0.370083	
C	Diameter	57.84867	57.72917	-	0.119497	

We identify the optimum values for the involved parameters as those corresponding to the highest values of S/N ratio. Comparing the means of S/N ratio we deduce the levels corresponding to the optimum values as:

- level 1 for the laser power, namely 800W;
- level 2 for the speed, namely 10 mm/s;
- level 1 for the spot diameter, namely 2.4 mm.

As one can see from the above graphic the last parameter has not a big variation, if we compare the mean of its S/N ratio with the one of the first parameter, which has a S/N ratio which varies a lot. This small variation suggests the fact that there are not big differences between the two regimes of work (operating modes). Same thing can be said if looking at the last column of Table 5.

Further, a statistical analysis of variance (ANOVA) is made in order to find out which process parameter is statistically significant and to identify the relative importance among them.

The parameters used when making the analysis of variance are:

- the Mean Square Between, noted MSB, which represents a variation between groups, more exactly the variation of group means around the general mean, evaluated as the sum of squares between, noted SSB, divided by the corresponded degrees of freedom (it measures the variation between groups);
- the Mean Square Within, noted MSW, which represents the variation inside all groups, evaluated by dividing SSW (the sum of squares within) to the corresponded degrees of freedom;
- F test, which represents the ratio between MSB and MSW for each parameter, it tells which design parameters have significant effect on the studied characteristic.

The above parameters can be found in any book related to the analysis of variance subject. In Table 6 we present the results of the analysis of variance.

Table 6. ANOVA results.

Symbol	Parameter	Degrees of freedom	SSB	SSW	MSB	MSW	F	Ranking
A	Power	2	0.324804	0.451628	0.162402	0.075271	2.157555	1
B	Speed	2	0.207042	0.56939	0.103521	0.094898	1.090862	2
C	Diameter	1	0.031732	0.7447	0.031732	0.106386	0.298276	3

A greater value for F means a controllable factor with higher importance. From the above table we can see that when we are interested in finding the optimum regime of work for obtaining the highest value for the microhardness, the most important parameter is the laser beam power, followed by the scanner velocity and then by laser spot diameter.

5. Confirmation test or experimental verification

Experimental verification is the last step in Taguchi method. The confirmation test is made in order to verify the estimated result with the experimental one. If the optimal combination of the levels can be found in the orthogonal array, the confirmation test is not required. Taguchi method establishes for our first study, focused on obtaining a higher microhardness of the surface layer, the following optimum combination of process parameters: 800W for the laser power, 10 mm/s for the scanning speed and 2.4 mm for the laser spot diameter. In our case the confirmation test is necessary because the orthogonal array doesn't contain a line with the mentioned combination of parameters levels.

In order to validate the results a new experiment with the optimum levels is performed. The maximum value obtained for the microhardness was 912 $HV_{0.05}$.

We notice that the value obtained at the confirmation test, is a value much bigger than the maximum microhardness obtained before, which was only of 830 $HV_{0.05}$, as we can see from Table 4.

6. Taguchi method and ANOVA results for optimal parameter setting – case of multiple responses (higher microhardness and depth of hardening)

Usually, in order to get a high quality for the necessary technological process we are interest not in only one characteristic of the sample but in obtaining desired values for many of them. In this paper we have applied Taguchi method also for finding the optimum levels of the controllable factors considering two characteristics: the maximum microhardness, and the high value for the depth of hardening.

We have combined the tools offered by the Taguchi method with those used in multi-criteria decisions making in the herein approach. For taking into account both characteristics we consider the utility concept, as in other papers dealing with the case of multiple responses, as for example [7].

Denoting by η_1 the S/N ratio for the microhardness and by η_2 the S/ N ratio for the depth, the global utility ratio is given by:

$$\eta = w_1\eta_1 + w_2\eta_2,$$

where w_1 and w_2 are the weights of the two characteristics, which depend on their importance and have positive values less than 1, with the sum 1. In this paper we have considered that the mentioned characteristics have both the same importance and so $w_1 = w_2 = 0.5$.

Doing the same study as before, but now considering multiple responses, made up by the harness and the depth of hardening, we get the following results, presented in Table 7 (multiple responses and the global utility S/N ratio), Table 8 (the mean of the global S/N ratio for each level), and Table 9 (ANOVA results). In Fig. 4, we have performed the comparison between the means of the global utility S/N ratio for each level and parameter.

Table 7. Multiple responses of experiments from L9 array, and evaluated S/ N ratios.

Nr. exp	Power	Speed	Diameter	Micro hardness	S/N ratio microhardness	Depth	S/N ratio depth	Global S/ N ratio
1	800	5	2.4	760	57.61627	834	58.42332	58.03121
2	800	10	4	830	58.38156	267	48.53023	53.45589
3	800	15	2.4	802	58.08349	584	55.32826	56.70587
4	1000	5	4	775	57.78603	933	59.39763	58.59183
5	1000	10	4	762	57.6391	600	55.56303	56.60106
6	1000	15	2.4	780	57.84189	723	57.18277	57.51233
7	1200	5	4	738	57.36113	1200	61.58362	59.47238
8	1200	10	2.4	781	57.85302	917	59.24739	58.5502
9	1200	15	4	748	57.47803	667	56.48252	56.98027

Table 8. Global S/N ratio for each level.

Symbol	Factor	Mean global S/N ratio (dB)				Total mean value for S/N ratio
		Level 1	Level 2	Level 3	Max distance	
A	Power	56.06433	57.56841	58.33428	2.269959	57.32234
B	Speed	58.69847	56.20239	57.06616	2.496087	
C	Diameter	57.6999	57.02029	-	0.679616	

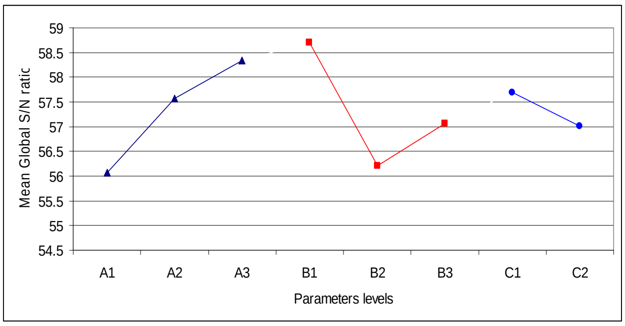

Fig. 4. Mean values of global S/N ratio for parameters, according to their levels.

Table 9. ANOVA results.

Symbol	Parameter	Degrees of freedom	SSB	SSW	MSB	MSW	F	Ranking
A	Power	2	8.001548	16.24565	4.000774	2.707609	1.477604	2
B	Speed	2	9.641003	14.6062	4.820501	2.434367	1.980187	1
C	Diameter	1	1.026395	23.22081	1.026395	3.317258	0.309411	3

As one can see optimum levels for the controlled factors are: level 3 for the laser power, level 1 for the speed and level 1 for the spot diameter. So the optimum operation regime is obtained choosing1200 W for laser power, 5 mm/s for speed, 2.4 mm for spot diameter.

The results in Table 9 show that the most important parameter is in this case the speed, followed by laser power and then by laser spot diameter.

We see that the levels of the laser power, and of the scanning speed have changed and also their ranking, because laser power doesn't represent now the most important parameter. It was overpass by the scanning speed.

The optimum level for speed is lower than in the first situation, when the objective was to obtain only a higher value for the microhardness, because, for a better penetration the laser wave interaction time with the material needs to be longer. The power of the laser has to be greater than in the first case in order to get a sufficient thermal gradient to penetrate deep layers.

Setting the parameters at the optimum levels: 1200 W, 5 mm/s and 2.4 mm, a new experiment is done. The experimental values obtained for the microhardness and the depth of hardening are: 750 $HV_{0.05}$, 1090 μm. The microhardness and the depth of hardening were compared with the predicted values, noted y_{pred} (for the microhardness) and z_{pred} (for the depth of hardening). The predicted values are deduced by using the following formulas [19]:

$$y_{pred} = \bar{y} + \sum_{j=1}^{3}\left(\bar{y}_j - \bar{y}\right),\; z_{pred} = \bar{z} + \sum_{j=1}^{3}\left(\bar{z}_j - \bar{z}\right)$$

where $\bar{y}$, and $\bar{z}$ represent the mean value of the microhardness, respective of the depth of hardening, and $\bar{y}_j$ and $\bar{z}_j$ represent the mean microhardness/depth of hardening corresponding to the optimum level of parameter j, $j = \overline{1,3}$. We get: 753.933 $HV_{0.05}$ for microhardness and 1187.056 μm for the depth of hardening. We notice that the predicted values for the microhardness and the penetration depth are close to the experimental ones.

7. Conclusions

In this paper Taguchi method is applied to determine the optimal values of the most important parameters that influence a laser hardening process. The paper also highlights the possibility of using Taguchi method for finding optimum values of parameters in case of multiple responses. Two different situations were considered: the case when only one output characteristic was envisaged, namely the maximum microhardness of the hardened layer, and the case when two characteristics were monitored: microhardness and depth of hardening. Optimal values of the parameters: P (power), V (scanning speed) and d (spot diameter) were determined in both cases.

In order to estimate the importance of considered factors, the results were analyzed by the aid of the analysis of variance (ANOVA). The optimum setting of parameters depends on the desired objective, because these levels are different for the two cases, and also the parameters importance.

Based on this approach some influences of different variables on hardened layer depth and microhardness can be deduced. Among the most important we mention:

- for getting a maximum microhardness in the hardened layer the laser power needs to be at the lowest level, and it also represents the most significant factor;
- increasing power laser radiation increases the depth of the affected zones;
- for obtaining a sample with a higher microhardness and a greater depth of the hardened zone a smaller value for the scanning speed is necessary, and the scanning speed is the most important parameter in this case.
- the spot diameter is not a significant factor for any of the cases, but using a smaller spot diameter, is more important in case when both characteristics are considered, so when a greater depth of the hardened zone is desired;

So, this paper points out that the Taguchi method, is not only a very powerful and inexpensive technique in quality engineering but, accompanied by the analysis of variance represents a very useful approach for a better understand of the process itself.

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