TAGUCHI'S QUALITY LOSS FUNCTION AND EXPERIMENTATION PLAN USED IN WEDM

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ABSTRACT: The paper outlines – in an original manner – the relevance of implementing quality-related concepts promoted by Genichi Taguchi in WEDM. The introduction briefly draws forth G. Taguchi's main contributions to the field of quality, emphasizing the quality-loss function and the Taguchi experimentation plans. Then, the authors show the implications of the Taguchi method to the design of a product, especially in setting nominal values and quality-specific tolerances. We exemplify by showing how to design an adjustment by minimizing the quality-loss function.Afterwards, we indicate how a manufacturing process should be run, in order to achieve parts that conform to Taguchi's approach. We present the way of grouping and the dispersion of quality characteristics of the parts manufactured according tothis approach. In order to efficiently exploit the products, we evince the methodology of Taguchi's experimentation plans for manufacturing parts using wire electrical discharge machining (WEDM). The of these plans as compared to the classical ones are also studied, with regard to their efficiency in optimizing the use of the products. Finally, conclusions regarding the usefulness of these concepts and the authors' interpretations are drawn.
KEYWORDS: Taguchi's quality loss function, Taguchi method, Taguchi experimenting plans, WEDM

1. PREAMBLE

Today, many manufacturers worldwide are paying increasing attention to quality issues for a variety of reasons. Since goods are a product of manufacturing processes, their quality depends directly on the quality of the latter. Subsequently, many recent studies have concentrated on improving the quality of the manufacturing processes.

Concepts developed by Japanese quality specialists regarding the consistency of products differ from those raised by their western counterparts. This suggests the possibility of economic losses, financially measurable, even when the products are obtained at the limit of the tolerances prescribed.

One of the greatest exponents of the Japanese school of quality is, undoubtedly, Doctor Genichi Taguchi. His major contribution is his entwinement of engineering techniques with mathematical statistics in order to achieve the rapid repayment of quality costs, seeking the optimization of the product design and manufacturing processes, with positive effects on the exploitation of products. He is owed tribute for defining the quality-loss function and the signal-to-noise ratio, both paramount applications to the amelioration of costs.

Approaching the quality issue in Taguchi's manner, a.k.a. the Taguchi method, occurred in the US during the 1980s. First, it was adopted by the AT&BELL Laboratories, followed by Ford Motors and Xerox.

Doctor G. Taguchi contributed to the development of the American Supplier Institute, whose purpose was to increase the application range of his methods and ideas. The latter have now been adopted by hundreds of companies across the US. Taguchi's approach has only flourished after 1990 in Western Europe, while here in Romania it is almost never used. Consequently, Romanian Universities are called out to promote this modern approach, with a view of smoothing the existing lags between our country and more developed economies.

2. THE IMPLICATIONS OF TAGUCHI'S APPROACH ON PRODUCT DESIGN

The quality-loss function is one of Taguchi's main contributions, which defines quality as a money-saving characteristic for both the manufacturer and the end user at a global and social scale. This being the case, it is natural that we be preoccupied in lowering quality-related losses even from the product design stage.

Genichi Taguchi has issued a simplifying hypothesis, which states that loss is proportional to the square of the characteristic's deviance from the target value. G. Taguchi's quality-loss function is defined as follows:

$$L(y)=k(y-y_N)^2 \quad (1)$$

where: $L(y)$ expresses the unitary loss, measured in monetary units; y is the value of the measured characteristic; y_N represents the nominal value, i.e.the target value, and *k* is a financial valorization constant, whose rate depends on the case under discussion.

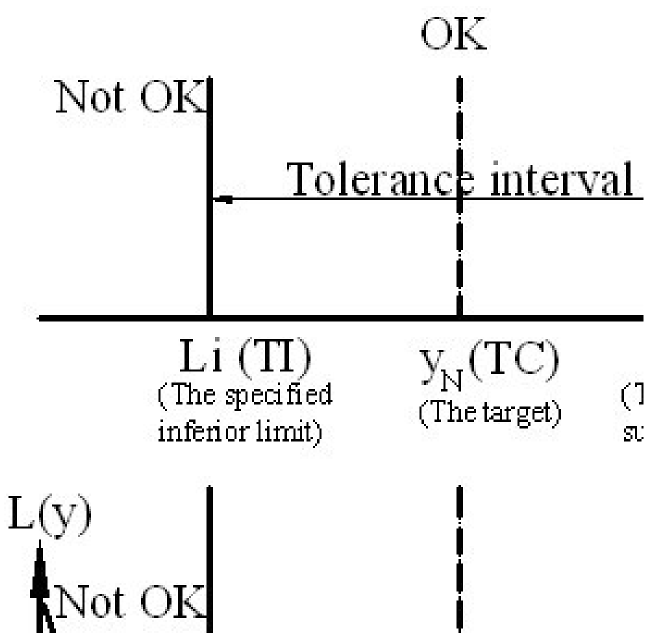

Figure 1. The relationship between the tolerance interval and Taguchi's approach

It can be noticed that the quality-loss function varies for different quality characteristics within the tolerance bounds prescribed by the classic approach. Through this function, G. Taguchi illustrates the idea that loss is a continuous function of the deviation, as compared to the target value and that this deviation fails to appear abruptly upon surpassing the bounds of a tolerance, which is often randomly defined. The loss is smallest when $y=y_N$, and it soars when the values vary: slowly at first, then more and more rapidly, as they diverge from the target value.

The western industry is always concerned with following tolerances, while failing to take into account their dispersion according to the targeted nominal value. One of the advantages of Japanese companies is that they are increasingly interested in achieving the targeted values and reducing dispersions progressively.

The 'quality-loss function' allows us to quantify the quality of a single given part or product. In the case of mass manufacturing we wish to evaluate the average quality of a batch or sample of products. In order to achieve this, we utilize the mean of the $(y_i-y_N)^2$ values, known as standard deviation, where y_i represents the measured values for n parts of the batch: $y_1, y_2, \ldots y_n$ and y_N the nominal value. We thus obtain:

$$L(y) = k[s^2+(\bar{y}-y_N)^2] \quad (2)$$

where:*s* represents the standard deviation for the measured values: $y_1, y_2, \ldots y_n$ and $\bar{y}$ the arithmetic mean of the $y_1, y_2, \ldots y_n$ measured values. There is a single product that leads to the particularization of relation (1) and results in the standard value (s=0).

It is obvious that minimizing loss means reducing the dispersion around the average value corroborated with the lessening of the average deviation against the nominal value. The best product is the one endowed with the targeted nominal value. The true way of minimizing quality loss is to reduce the deviances against the target values and not set 'compliant / non-compliant' limits.

L(y) takes different forms if the optimization criteria need maximizing or minimizing. When we need to minimize the criteria, the quality-loss function can be calculated using the following relation:

$$L(y) = k[s^2+(\bar{y})^2] \quad (3)$$

And, when we wish to minimize a criterion, the quality-loss function becomes:

$$L(y) = k\cdot(1/(\bar{y})^2\cdot[1+3\cdot(s^2/\bar{y})^2] \quad (4)$$

Subsequently, upon designing a product, it is necessary that quality characteristics be correctly limited, according to this new approach. For dimensional tolerances, for example, it is opportune that the nominal value come with bottom inferior and superior deviances, equal and of opposite signs.

In this case, we can take advantage of a broader field, located around the nominal value, given acceptable quality losses. If we dimension by using a maximum amount of material – a very common practice in Romania – then the previously-mentioned field becomes reduced by half. Consequently, we must reconsider the dimensions and tolerances prescribed on our drawings. We might have to adapt the system of fits currently in use to the particularities of Taguchi's approach.

By way of exemplification of the quality-loss function, let us consider a sliding fit (Figure 2) that conforms to the present system of fits.

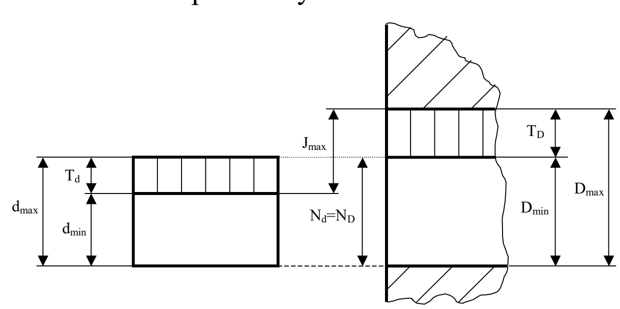

Figure 2. Sample sliding fit

The fit will work correctly for the product that specifies it, until the allowance reaches the maximum rated value (j_{max}). If the two components are manufactured at the nominal value ($N_d = N_D$), the fit will yield a maximum lifespan, since the wear must cover both parts' tolerances until the maximum allowance is reached. If we consider the extreme situation, when we manufacture the parts to the limit – that is to say the spindle's diameter is minimum (d_{min}) and the hole's is maximum (D_{max}) – the fit's lifespan is minimum. Although the two components are manufactured within the prescribed tolerances – even if barely – it won't take long until the wear will exceed the maximum allowance, which requires the replacement of both the fit's components. In the first case, the losses will be minimum for both the manufacturer and the beneficiary and maximum in the second case.

3. THE MANAGEMENT OF MANUFACTURING PROCESSES ACCORDING TO THE TAGUCHI APPROACH

Manufacturing processes are to be managed and run to achieve compliant parts within prescribed tolerances, minimizing financial losses that lead from the quality-loss function. This means reconsidering certain present-day concepts and practices. If we consider a manufacturing process's capability and dynamic stability concepts, we can evince several possible alternatives to the manufacturing processes, as shown in Figure 3.

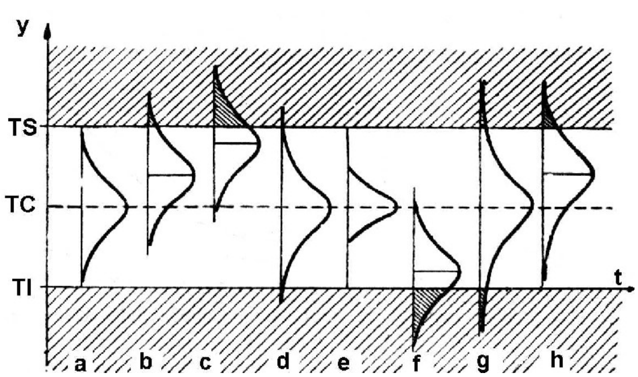

Figure 3. Alternatives to the manufacturing processes

Three of the cases presented in Figure 3 – a, e, and g – represent centered manufacturing processes. In the first case (a), the dispersion of quality characteristics covers the entire tolerance, in the second (e), the dispersion goes down to values neighboring the center of the tolerance interval, while the process shown in g is imprecise and outside the prescribed limits.

According to the classic approach, case (a) would be considered a precise and centered process because quality characteristics are centered on the average value (TC) and the dispersion of quality characteristics (6σ) is ultimately equal to the tolerance (T =TS –TI). Case (a) is also considered to be uneconomical, by employing too precise a fit for the prescribed quality characteristic.

In order to minimize the quality-loss function, Taguchi's approach only admits of a processing whose distribution is similar to that of case (e), corroborated with the choosing of the nominal value equal to the average mean of the quality characteristic. The other cases presented in Figure 3 are unaccepted by either of the two approaches, since they are off-centered (b, c and f), imprecise (d, g) or off-centered and imprecise (h) manufacturing processes.

So as to reduce the quality losses to the minimum:

- manufacturing processes are to be centered on the quality characteristics' nominal value, and
- the dispersion of the values that are obtained are to be as small as possible and centered on the nominal value.

4. THE EFFICIENT UTILIZATION OF PRODUCTS. TAGUCHI EXPERIMENTATION PLANS USED IN WEDM

If products are designed and manufactured according to Taguchi's approach, then losses during their utilization will be lowest for the users. If we consider the warranty period and also the unfavorable implications resulting from the lack of quality regarding customers' reaction, we can almost predict the eradication of loss the manufacturer might suffer from, regarding the utilization of the manufactured goods.

To exemplify, let us go back to the sample fit from Figure 2. If the components of the fit are manufactured at the nominal value, the fit has the longest lifespan. The user will be happy with the product, appreciating its high reliability. At the same time, the manufacturer will not be involved in the placing out of operation of the fit, since it'll probably occur outside the warranty interval. If the two components are designed to achieve the maximum allowance, then, as a consequence of wear, it'll go over the limit. The faulty fit still in warranty will cause distress to the end user, first of all, since that means replacing it while the device that contains it is rendered useless. On the other hand, the maker will also incur losses, as a consequence of repairing costs. Furthermore, the manufacturer will sustain adamagedreputation due to the clients' perception of the low qualitywhich is being offered.

Even if a product is designed and manufactured according to Taguchi's principles, the issue of efficient utilization still arises. This means the product is supposed to function according to some prescribed parameters, so that it meets the user's demands. Let us consider any given product, from the perspective of the systematic approach (Figure 4). During periods of utilization, it will offer the user the following response functions: y_1, y_2, ...y_m, according to the controlled factors (i.e. running parameters): x_1, x_2, ... x_n, considering they become visible through controlled and unrequired input variables: μ_1, μ_2, μ_3, ... μ_r and uncontrolled-unrequired input variables: z_1, z_2, z_3, ... z_p. The latter two categories of variables are referred to as noises.

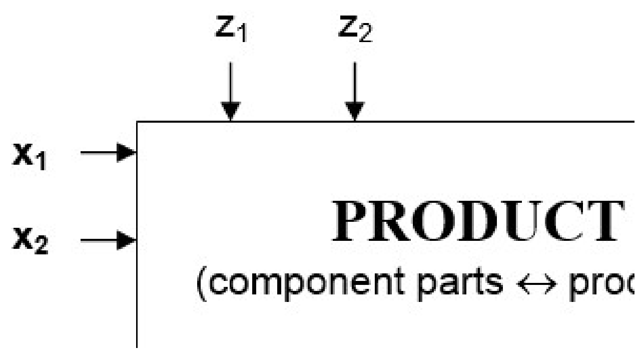

Figure 4. The functioning of a product, according to the systemic approach

The main difference between the classic approach and Taguchi's resides in the way we consider the influence of noises. The classic approach seeks to purge noises, a pricy and usually impossible task. Taguchi's method proposes a more realistic approach. It is considered that noises exist anyhow, and they must be regarded accordingly. However, they can only be known and controlled following the testing of the product under real conditions. Thus, G. Taguchi came up with the so-called Taguchi's experimentation plans. They allow the optimization of the functioning of a product, subsequent to certain fractioned factorial experiments, during which we take into account, besides the desired values of the response functions, their undesired variance, due to noises which impact upon the functioning of the product.

We use a compound performance indicator, called signal-to-noise ratio, which can help find combinations of functioning parameters that need be controlled, and which prove to be most insensitive to noise factors. On the other hand, if we express the ratio in decibels, regardless of the nature of the measurements taken (millimeters, volts, etc.), we can objectively compare the performances of several characteristics undergoing simultaneous optimization.

It is obvious that, in order to be able to identify and calculate the variability corresponding to a configuration of controlled factors, we must measure the characteristic(s) that need(s) optimizing, considering a production sample above 1.

The signal-to-noise (S/N) ratio is the synthetic measure of a product's performance, which takes into account both the average and the dispersion of outputs, both wanted – which represent the "signals" – and unwanted– the "noises".

The signal-to-noise ratio is endowed with the additive property, which means the sum of the factors' effects is equal to the combined effect. It also features the property by which the maximization of the performance index is equated to the minimization of quality loss.

The mathematical expression of the signal-to-noise ratio is:

$$S/N = 10 \log[(\bar{y}/s^2) - 1/n] \text{ [dB]} \quad (5)$$

where:

- $\bar{y}$ – represents the arithmetic mean of the measured values;
- s – the standard deviation of the measured value;
- n – the number of measurements taken.

The bigger the S/N ratio is, the smaller the general loss, (L(y)) and the greater the performance of the optimized process or product. The S/N ratio takes different forms depending on whether the optimization criterion needs maximization (6) or minimization (7):

$$S/N = -10 \log[(1/\bar{y}^2)\cdot(1+(3\cdot s^2/\bar{y}^2)] \text{ [dB]} \quad (6)$$

$$S/N = -10 \log[s^2+(\bar{y}^2)] \text{ [dB]} \quad (7)$$

The planning of the experiments itself is based on orthogonal, fractional, standard experimentation matrixes, or based on triangular tables or linear graphs described in specialty papers. The results are represented via line segments, a very suggestive and easily explainable method, regardless of the number of controlled factors. The longer the segments, the more influential the considered factor is.

To exemplify, let us look at the optimization results of a manufacturing machine, which we consider to be the product here, whose maximization of the manufacturing productivity (Q_w) we seek. The manufacturing process considered refers to the manufacturing of miniature revolving surfaces using wire electrical discharge machining (WEDM). Tables 1 and 2 present the tests carried out regarding the productivity of manufacturing and the responses of the manufacturing machine, using an L_8 Taguchi experimentation matrix. The latter allows us to analyze 6 influencing factors (parameters): A, B, C, D, E, F and an interaction (BC).

Since there are two levels, there will be two indexes: 1 and 2. Each experiment ($E_1 \div E_8$) has generated 5 responses ($i_1 \div i_5$). The effects on the measured value (the productivity of processing) and the S/N ratio are presented in Figures 5 and 6.

Table 1. The results of the experiments regarding processing productivity

Experim. No.	Controlled factors						Interact.	The measured values for Q_W [mm^3/min]					Calculated values		
	A	B	C	D	E	F	BC	i1	i2	i3	i4	i5	Mean	Var.	S/N
E1	1	1	1	1	1	1	1 1	1.82	1.92	1.76	1.85	1.7	1.81	0.084261	5.102762
E2	1	1	1	2	2	2	1 1	2.41	2.56	2.38	2.57	2.51	2.486	0.086776	7.870737
E3	1	2	2	1	2	2	2 2	12.35	12.26	12.52	12.39	12.48	12.4	0.103682	21.85715
E4	1	2	2	2	1	1	2 2	9.25	9.4	9.18	9.34	8.97	9.228	0.166943	19.26298
E5	2	1	2	1	1	2	1 2	1.86	1.76	1.63	1.68	1.92	1.77	0.12083	4.853304
E6	2	1	2	2	2	1	1 2	3.71	3.89	3.62	3.94	4.01	3.834	0.163187	11.58348
E7	2	2	1	1	2	1	2 1	6.23	6.51	6.46	6.18	6.49	6.374	0.156301	16.03859
E8	2	2	1	2	1	2	2 1	8.06	8.11	8.24	8.15	8.02	8.116	0.085029	18.17525
General means													5.75225	0.120876	13.09303

Table 2. Processing productivity responses

The effect on the measured values		Factors	The effect on the S/N ratio		Interaction	The effect on the	
Level 1	Level 2		Level 1	Level 2		Measured value	S/N ratio
0.72875	-0.72875	A	0.430376	-0.43038	B1C1	0.72875	0.430376
-3.27725	3.27725	B	-5.74046	5.740462	B1C2	-0.72875	-0.43038
-1.05575	1.05575	C	-1.2962	1.296197	B2C1	-0.72875	-0.43038
-0.16375	0.16375	D	-1.13008	1.130079	B2C2	0.72875	0.430376
-0.52125	0.52125	E	-1.24446	1.244458			
-0.44075	0.44075	F	-0.09608	0.096079			

Based on the representations shown in Figures 5 and 6, we can choose convenient values for the influencing factors so that the considered product, namely the manufacturing machine, can runwithmaximum productivity. The combination of factors is adopted mainly according to the S/N ratio. Thus, in this case, we adopt the following combination: A_1, B_2, C_2, D_2, E_2, F_2.

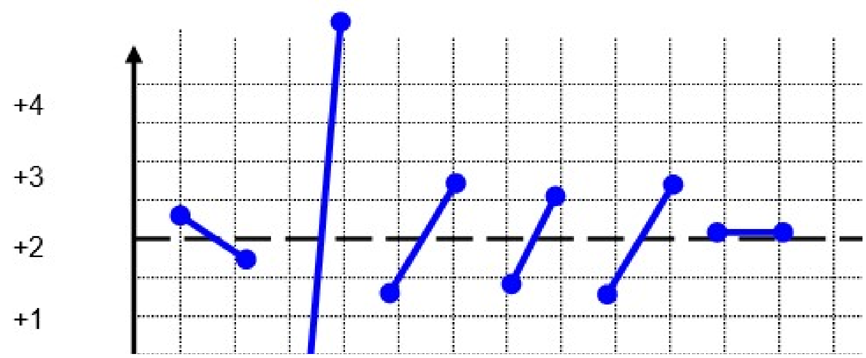

Figure 5. The effects on the S/N ratio

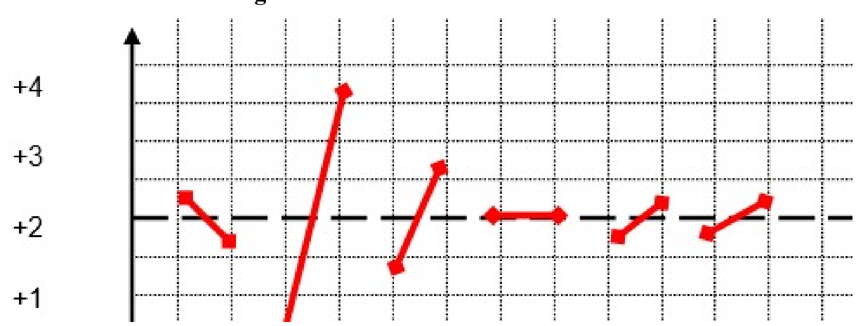

Figure 6. The effects on the measured value of productivity

The method is easy to implement; it doesn't require special software applications, instead it only demands a pocket calculator and Excel worksheets, based on calculus relations found in specialty papers.

5. CONCLUSIONS

The utility of Genichi Taguchi's concepts to the designing, execution and exploitation of products is unquestionable. They stimulate the improvement in quality of products through the reduction of loss at every stage in the lifecycle of a product.

Using the quality-loss function can lead to the rethinking of a product's design, and it can also improve the way manufacturing processes are run and controlled. In other words, Romanian companies can embrace a new way of formulating manufacturing practices.

The Taguchi experimentation plans allow the optimum utilization of designed and manufactured products, all this under real working conditions, ensuring their economicutilization.

Concepts specific to Taguchi's approach are easily implemented, assuming we relinquish the old habits and adopt a new organizational culture. It is necessary that they be promoted, and universities are the first tasked with this mission. Implementing these concepts will lead to undeniable benefits for any industrial user.

6. REFERENCES (HEADING 1)

1. Alexis, J., *Metoda Taguchi înpracticaindustrială. Planuri de experienţe*.,EdituraTehnică,Bucureşti, (1999).
2. Deneş, C.,*Consideraţiiasuprastabilităţiidinamice a proceselor de fabricaţie. Tehnologii Moderne, Calitate, Restructurare*, Vol. 1, Chişinău, (2001).
3. Oprean, C. ş.a.,*Managementulintegrat al calităţii*. EdituraUniversităţii „Lucian Blaga” din Sibiu, (2005).
4. Ţîţu, M., Nanu, D. *Bazele prelucrării cu energii concentrate. Editura Universităţii Lucian Blaga Sibiu*, ISBN 973-651-513-3, 2002.
5. Țîțu, M., Oprean, C., Boroiu, Al. *Cercetarea experimentală aplicată în creșterea calității produselor și serviciilor,* Colecţia Prelucrarea Datelor Experimentale, Editura AGIR, ISBN 978-973-720-362-5, 684 pagini, București, 2011.