Widening of 10NiCr180 Stainless Steel – Process Simulation and Cutting Torque Mathematical Models

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Abstract: - Stainless steels’ impressive mechanical characteristics resulted in their use to various and important industrial fields that has been continuously expanded lately. There are many cases when widening already existing hole is required so, attention to the processes involved has been given. This paper presents aspects of the simulation and the experimental procedure developed in order to determine new and more adequate mathematical models of cutting torque, in widening 10NiCr180 stainless steel.

Key-Words: - torque, widening, stainless steel, mathematical model, regression, simulation

1 Introduction
Stainless steels have been “discovered” almost one hundred years ago and since then, their application fields are more and more versatile as well as challenging. One reason for these is because of their important physical and mechanical characteristics, specially, their high corrosion resistance to various chemical agents and their impressive good look [2].

Many times, the stainless steel raw parts need machining, in order to get shape, dimensions and surface roughness required. These steels are very tough, with low thermal conductivity and, while machining, determines sever wear of the cutting tool, as well as, high value cutting forces [6].

Being expensive materials, detailed research on their machinability has to be done, so that optimum process parameters would be involved and, thus, high productivity and low cost stainless steel parts could be obtained.

One important aspect of material’s machinability is represented by the cutting force and torque values – in drilling and widening,, meaning the higher the values, the lower machinability and the poorer energy efficiency use [3]. Specific literature presents relationships involving torque values but, when experimentally checking them, high difference of the modeled ones from the real experimental values can be noticed [5].

When experiments were carried out, once the values of $M_C$, $m_X$, $m_Y$, $m_Z$ known, the same values of cutting tool’s diameter, cutting depth and

2 Research Methodology
Mathematical relationship on cutting torque in widening stainless steel materials, presented by most of the specific literature is:

$$M = C_M \cdot D^{m_X} \cdot f^{m_Y} \cdot a_p^{m_Z} \quad [Nm] \quad (1)$$

where:
- $M$ – the widening torque;
- $D$ – the diameter of the widening tool, [mm];
- $f$ – cutting depth (the half difference of the hole’s final and initial diameters) [mm];
- $a_p$ – cutting feed, [mm/rot];
- $x_M$, $y_M$, $z_M$ - polytropic exponents;
- $C_M$ - constant.

When experiments were carried out, once the values of $C_M$, $x_M$, $y_M$, $z_M$ known, the same values of cutting tool’s diameter, cutting depth and
cutting feed but, different values of cutting speed resulted in different cutting torque values. So, one could think that the parameter not mentioned by relation (1) and meaning cutting speed, should have an important role in torque values’ prediction.

That is why, the idea of a new relationship regarding cutting torque and more specific process independent variables has proved to be opportune. So, the new independent variable involved is the cutting speed \( v \) [mm/rot] and the resulting original proposed mathematical model is:

\[
M = C_M \cdot D^{5M} \cdot f^{y_M} \cdot a_p^{z_M} \cdot v^{w_M} \quad [Nm] \quad (2)
\]

where: \( v \) is peripheral rotational speed of the widening tool, usually mentioned as cutting speed [m/min];

\( w_M \) - polytropic exponents;

Determining the constants and polytropic exponents’ values needs that relation (2) is of linear type and so, by logarithm, it turns into linear expression as:

\[
\lg M = \lg C_M + x_M \cdot \lg D + y_M \cdot \lg f + z_M \cdot \lg a_p + w_M \lg v \quad (3)
\]

3 Process Simulation

Widening a hole involves the existence of a previously obtained one so, it is important that the axes of initial hole and widening tool to be the same. That is why, whenever possible, simulation of the process it’s worth be done, in order to avoid errors of holes’ position and even, length or diameter.

So, there has been carried out a process simulation, considering rectangular shape samples, each of them with four holes, all of them being, in fact, used in experiments.

The software used for simulation was isy-CAM, which is specific to Isel-automation manufacturing systems [8]. It operates under Windows and is made of two parts:

- isy-CAM CAD part (for designing and modeling parts 2D or, 3D)
- isy-CAM CAM part (for machining on CNC machine-tools with 3, 3.5 or 5 axes);

Some images of the drilling process simulation can be seen in:

- figure 1 – selecting cutting tool type,
- figure 2 – holes’ axes position,
- figure 3 – phases of the simulated process
  a. \( \rightarrow \) sample before widening
  b. \( \rightarrow \) sample while widening the first hole

**Fig. 1** Isy-CAM – selecting cutting tool

**Fig. 2** Isy-CAM – holes’ axes position

**Fig. 3** Isy-CAM – widening process simulation
4 Mathematical Models

New mathematical models to be obtained involve experimenting followed by determining of constants and polytropic exponents.

4.1 Experiments

A special experimental system was designed and used in experiments, its most important components being presented above – see figure 4.

→ The machine tool (1) was a drilling machine, coded GC032DM3, whose electric motor had 3.5 kW power. The working table dimensions were 420 × 480 (mm) and the main spindle had a no. 4 Morse cone. Possible rotational speed range values of the drilling tool were 70 ÷ 1400 [rot/min], with 12 geometrical ratio levels variation and possible cutting feed values were 0.12; 0.20; 0.32; 0.50 [mm/rot].

→ The cooling/lubricating fluid was 20% P emulsion.

→ Cutting tools (2) were made of Rp5 material with no. 62 Rockwell hardness and. diameter’ values of: \( \Phi_1 = 16 \); \( \Phi_2 = 24 \) [mm], widening an initially holes of 12 mm and 16 mm diameters.

→ Special rotational device (3), for adequate measuring of torques; its most important element consists of an elastic sleeve with four resistive transducers, each inclined by 45° with respect to horizontal and vertical axes attached to it.

→ IEMI type electronic bridge (4) which, was coupled to a data acquisition system, using the graphical programming LabVIEW software (5), whose graphical program can be seen in figure 5.

→ Studied material was 10NiCr180, whose chemical structure is presented in Table 1, while its mechanical characteristics are mentioned in Table 2.

Table 1 Chemical Structure.

<table>
<thead>
<tr>
<th>C [%]</th>
<th>Ni [%]</th>
<th>Cr [%]</th>
<th>Mn [%]</th>
<th>Si [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>9.50</td>
<td>18.40</td>
<td>1.90</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Table 2 Mechanical Characteristics.

<table>
<thead>
<tr>
<th>Tensile Strength, ( R_m ) [N/mm²]</th>
<th>Flow Strength, ( R_{0.2} ) [N/mm²]</th>
<th>Relative Elongation ( \delta ) [%]</th>
<th>Hardness, HB</th>
</tr>
</thead>
<tbody>
<tr>
<td>746</td>
<td>484</td>
<td>34.2</td>
<td>202</td>
</tr>
</tbody>
</table>

Experimental values obtained for cutting torque, in widening 10NiCr180 stainless steel are shown in Table 3.

Just for comparative reasons, there have been registered the torque values, under the same experimental conditions but for an etalon material considered as reference, meaning OLC 45 carbon steel.
3.2 Obtaining Mathematical Models

As result of the experiments carried on, the equations system required for model’s coefficients determination (when considering the first five experiments) are as follows:

\[
\begin{align*}
\lg 17.7 &= \lg C_M + x_M \cdot \lg 24 + y_M \cdot \lg 4 + z_M \cdot \lg 0.12 + w_M \cdot \lg 16.88 \\
\lg 24.9 &= \lg C_M + x_M \cdot \lg 24 + y_M \cdot \lg 4 + z_M \cdot \lg 0.20 + w_M \cdot \lg 26.75 \\
\lg 31.9 &= \lg C_M + x_M \cdot \lg 24 + y_M \cdot \lg 4 + z_M \cdot \lg 0.32 + w_M \cdot \lg 16.88 \\
\lg 41.1 &= \lg C_M + x_M \cdot \lg 24 + y_M \cdot \lg 6 + z_M \cdot \lg 0.20 + w_M \cdot \lg 16.88 \\
\lg 64.4 &= \lg C_M + x_M \cdot \lg 16 + y_M \cdot \lg 2 + z_M \cdot \lg 0.20 + w_M \cdot \lg 11.25
\end{align*}
\]

\[\text{(4)}\]

Solving the equations system results in the real values of \( C_M \) constant and \( x_M, y_M, z_M, w_M \) polytropic exponents [5]. Thus, knowing that initial dependence relationship was exponential and that the ones used in equations system (4) are obtained from the first one, by logarithm, the mathematical model of the cutting torque, in widening 10NiCr180 stainless steel is:

\[ M = 0.42 \cdot D^{0.94} \cdot f^{0.6} \cdot a_p^{1.32} \cdot v^{0.07} \text{ [Nm]} \]  \[\text{(5)}\]

Because of the fact that relation (5) was obtained by solving classical equations system – meaning five unknown parameters and five equations, one can think of trying to improve the obtained mathematical model. So, a real regression analysis and a designed experiments program should be considered.

A careful look on model (5) points out the fact that the strongest influence on torque value is that of cutting feed \((a_p)\), cutting tool diameter \((D)\) and cutting depth \((f)\), while the cutting speed \((v)\) has the least influence on it. That is why, these above mentioned three parameters should be considered as independent variables (input) while the dependent variable (output) would be the cutting torque values. The design of experiments should be the one specific to the regression analysis carried out with DOE KISS software (student version).

Considering the number of independent variables studied (3) and the software version available, there have been done experiments, according to a Full Factorial Design, two variation levels for each independent variable. As required [5], [6], coded values of the independent variables had to be considered so the, relationship of coded value \( x_j \), to natural value, \( z_j \), is:

\[ x_j = \frac{z_j - z_{\text{min}} + z_{\text{max}}}{z_{\text{max}} - z_{\text{min}}} \cdot \frac{2}{j = 1,2,3} \]  \[\text{(6)}\]
where: ‘min’ is for the minimum values and ‘max’ is for the maximum values.

Real and coded values of inputs are presented in table 4 while the applied experiment design and the experimental results obtained can be seen in table 5.

It is to be mentioned that each experience has been repeated five times, these involving that replicates number equals five.

**Table 4  Independent variables values**

<table>
<thead>
<tr>
<th></th>
<th>Real, ( z_j )</th>
<th>Coded, ( x_j )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting feed, ( a_p ) [mm/rot]</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>0.32</td>
</tr>
<tr>
<td>Cutting tool diameter, ( D ) [mm]</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>Cutting depth, ( f ) [mm]</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

**Table 5  Experiment design and obtained results**

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>( x_1 )</th>
<th>( x_2 )</th>
<th>( x_3 )</th>
<th>Drilling torque ( M ) [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>-1</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
<td>+1</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>+1</td>
<td>-1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>+1</td>
<td>+1</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td></td>
</tr>
</tbody>
</table>

Results of regression analysis, carried out with DOE KISS software, are shown in figure 6.

As an observation, it is pointed out the fact that regression coefficients with \( P \) (2 Tail) values higher than 0.05, are considered to have no significant influence on the output variable. So, all the considered independent variables have proven to significantly influence the dependent variable. More of it, all the inputs interactions do influence the output values.

So, the regression model obtained, with the coded values, \( x_j \), is:

\[
M = 18.738 + 6.9875 \cdot x_1 + 12.263 \cdot x_2 + 3.37375 \cdot x_3 + \\
+ 6.3125 \cdot x_1 x_2 + 2.7375 \cdot x_1 x_3 + 2.8125 \cdot x_2 x_3 + \\
+ 3.1125 \cdot x_1 x_2 x_3
\]

Considering relation. (6), as well as the data in table 4, it results the mathematical model with natural (real) values of the variables studied – see relation (8):

\[
M = 18.738 + 6.9875 \cdot \frac{a_p - 0.22}{0.1} + 12.263 \cdot \frac{D - 20}{4} + \\
+ 3.37375 \cdot \frac{f - 4}{2} + 6.3125 \cdot \frac{a_p - 0.22}{0.1} \cdot \frac{D - 20}{4} + \\
+ 2.7375 \cdot \frac{a_p - 0.22}{0.1} \cdot \frac{f - 4}{2} + 2.8125 \cdot \frac{D - 20}{4} \cdot \frac{f - 4}{2} + \\
+ 3.1125 \cdot \frac{a_p - 0.22}{0.1} \cdot \frac{D - 20}{4} \cdot \frac{f - 4}{2} = \\
= 113.458 + 10.75 \cdot a_p + 1.6114 \cdot D + 8.745 \cdot f + \\
+ 0.2188 \cdot a_p \cdot D + 64.125 \cdot a_p \cdot f - 0.5044 \cdot D \cdot f + \\
+ 3.8906 \cdot a_p \cdot D \cdot f
\]

**Fig. 6** DOE KISS regression analysis results
The software provides an “Expert Optimizer” meaning, it “offers” the independent variables’ values so that optimum value of the dependent variable to be obtained. An image of it is shown in figure 7. Also, a Pareto chart of coefficients, pointing out how strong the influence of each input, as well as their interactions, on the output values is can be seen in figure 8.

Fig. 7 DOE KISS Expert Optimizer

Fig. 8 DOE KISS Pareto chart of coefficients

4 Conclusion

Application fields of stainless steels have known an impressive extend, specially because of their special characteristics, such as: high corrosion resistance to various chemical agents, fire, heat resistance, impact resistance, hygiene, impressive good look.

When a stainless steel part is designed with holes of same, or various dimensions and precisions, often a machining procedure, like widening, is necessary. Cutting torque is an important parameter (output variables) of the process that can often be used for its optimization.

So, a research to determine new adequate models of the cutting torque in widening one highly used Romanian stainless steel – 10NiCr180 has been done and the results are presented by this paper.

There were carried out experiments under specially designed conditions, meaning: widening process simulation, experimental system designed; variation fields and values of studied variables established; designed the experiments and regression analysis techniques applied.

Two kind of mathematical models, for the cutting torque were obtained, one under sort of “elementary” conditions and the other under more accurate conditions, meaning design of experiments and regression analysis. Though all mathematical models determined, have proved to be adequate, and evidenced similar influence of independent variables (inputs) on the output. Once determined, the considered models were further checked, by more experiments – for different values of the parameters. All the experimentally obtained results were in good concordance with the model’s predicted values.

Further research should be developed so as to implement obtained mathematical models, into an automated optimization system of widening process.

References:
[2] Iliescu M, Vlase A., New Statistical Models of Cutting Tool Wear and Cutting Speed in Turning 20MoCr130 Stainless Steel, 10th WSEAS MACMESE’08, pag. 204-209, ISSN 1790-2769, Bucharest, Romania, November 7-9, 2008