Study on Machined Thermal Sprayed Coatings Adherence

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Abstract: - Thermal sprayed coatings represent a modern way of solving real important problems, like repairing worn parts working under severe wearing conditions or, ensuring efficient corrosion protection of parts used in sea, as platform, bridges, or obtaining high refractory surfaces. Most of the times, once obtained, these coatings need additional machining – by turning, grinding, etc. and it is of interest how, and, if, any of the machining parameters do influence one of their very important characteristic – adherence to the basic substrate. The paper presents a study on the adherence of metallized coatings, obtained from several Romanian thermal sprayed materials and submitted to exterior cylindrical turning.

Key-Words: - thermal sprayed coatings, metallizing process, cylindrical turning, adherence, transducer, sample

1 Introduction
Metallizing is the process of spraying molten metal, metallic oxides or ceramics, onto a previously prepared substrate. The material is melted in a flame, or into an electric arc or in a plasma jet and atomized, by a blast of compressed air, into fine spray [7]. When impacting a previously prepared surface, or the previous thermal sprayed layer, the molten material particles flatten out, crack (specially the oxides surroundings) and anchor onto the rough substrate thus, forming the metallized layer. By successive thermal sprayings, a lamellar, anisotropic structure is obtained. The bonds between particles, as well as their bond to the basic substrate are obtained by: particles cementing of surroundings oxides, welding micro-points and mechanical anchoring onto the impact surface’s roughness.

The sprayed molten particle that strikes the surface, flattens out and cools so, residual stresses do appear. When the multilayer structure – meaning thermal coating – is obtained, these residual stresses do sum up and, thus, a permanent internal stresses field exists. As result, the exterior coating is in tensile stress, while the basic material is in compressive stress – if considering exterior cylindrical thermal sprayed coatings.

When spraying onto flat surfaces, the residual internal stresses, within the coating, may produce a curvature of part’s the exterior sides while, if spraying onto interior cylindrical surface, there is the danger that multilayered structure falls off the basic substrate.

A schematic representation of metallized coating is shown in figure 1.

Fig. 1 Thermal sprayed coating [4]

Thermal sprayed coatings have very important mechanical characteristics, such as: hardness, compressive strength, porosity, wear resistance and, not the last, adherence.

Many times, in order to obtain specified geometrical precision conditions, after metallizing, some machining of the sprayed coatings is needed. One commonly used procedure (that, if carefully performed, does not harm the multilayered structure) is cylindrical turning. As the specific literature does not mention, if the machining parameters have any influence on coatings’ adherence, it has been considered useful a study on this topic [1]. In order to do this, a special transducers system has been designed.

2 Experimental Research
The studies were carried out on specially prepared samples, whose thermal sprayed materials were Romanian produces ones: MET 4, Inox 18-8, S12Mn2Si and Al-OI (alluminium steel alloy).
The metallizing process is using an electric arc for melting materials, whose initial shape is wired and, compressed air for spraying toward the previously prepared substrate.

The chemical structure of the metallizing materials, as well as some mechanical properties of the sprayed coatings are presented in Table 1.

The metallographic structure of the multilayered metallized structure is presented in figure 2, for each of the studied thermal sprayed materials [3].

The experiments samples are specially made ones, according to STAS 11684/4-83 specifications. Each thermal sprayed material had a corresponding sample, the ring zones being obtained by carefully turning.

### Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical Structure</th>
<th>HV 0.05</th>
<th>Porosity [% vol]</th>
<th>Steel Base Adherence [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET 4</td>
<td>(14 + 15) % Cr, (0,4 + 0,5) % C</td>
<td>370</td>
<td>7 + 9</td>
<td>47</td>
</tr>
<tr>
<td>Inox 18-8</td>
<td>8,8 % Ni, 18,9 % Cr</td>
<td>340</td>
<td>7 + 9</td>
<td>26</td>
</tr>
<tr>
<td>S12Mn2Si</td>
<td>max 0,12% C (1,8 + 2,2) % Mn max 0,15% Si</td>
<td>290</td>
<td>7 + 8</td>
<td>40</td>
</tr>
<tr>
<td>Al-Oi</td>
<td>99,5% Al + S10Mn1Ni2 (0,8 + 1,2) % Mn (1,8 + 2,2) % Ni</td>
<td>150</td>
<td>7 + 9</td>
<td>24</td>
</tr>
</tbody>
</table>

Figure 3 presents a sample, before experimenting and figure 4 presents a damaged sample – when turning process for obtaining the machined zones was not carefully performed, the thermal sprayed coating fallen off the basic substrate.

All the experiments were carried out according to standard specifications – involving testing the adherence of thermal sprayed coatings, by shearing failure of the coating. A schematic representation of a test is shown in figure 5.
As for real experimenting stand, it is mentioned that it has been used a hydraulic press, WE-60 and, there have been designed and manufactured some special intermediate elements – so as to be possible the monitoring of, both applied compressive force’s values and, of coating’s displacement, while the failure occurs. An image taken while experimenting is presented in figure 6.

In order to measure force’s and displacements values, there were used transducers – resistive type, for force measuring and inductive type, for displacements measuring. Before starting experiments, the transducers were calibrated and their calibrating equations were used for calculating real values of the involved parameters. Also, for complete, precise and more efficient measurements, a data acquisition system (AT-MIO-16L-9) was used, and LabVIEW soft-ware allowed the complete determination of studied values.

### 3 Experimental Results

As mentioned above, the target of this experimental study is to determine if the machining parameters do influence thermal sprayed coating adherence – to the basic substrate. So, the machining procedure considered, was exterior cylindrical turning – based on the fact that most of metallized layers machining is done by turning and, also, that, even when checking adherence the standard do mention exterior cylindrical thermal sprayed coatings.

The machining parameters values, meaning cutting speed, \( v \); cutting feed, \( s \) and cutting depth, \( t \) are shown in table 2. To notice that, there are shown, both real and coded values \((-1;+1)\), the last ones being used in statistic regression calculus, if a dependence mathematical model of adherence variable, should be obtained [2].
When experimenting, on each sample there were three metallized coating zones (as seen in figure 3 and figure 6) but, turning was done only on two of the ring shape zones, the third being considered “witness” – for comparing adherence results.

Some of the experimentally obtained results are presented in Table 3.

The LabVIEW data acquisition system (set for 5,000 measurements/second, for 20 seconds, each experiment) allowed plotting the curves of, both, force and displacement time variation (for each of the studied thermal sprayed coatings). Also, by “combining” the signals (from the two transducers type), it was possible to obtain the force - displacement graph, that points out, the way compressive force varies, while the metallized coating is falling off the basic substrate.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific elements</th>
<th>Experiments type - machining parameters coded values combination -</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force, when failing, F</td>
<td>reference (-1; -1; -1) (-1; -1; +1) (+1; +1; +1)</td>
</tr>
<tr>
<td></td>
<td>([\times 10^4 N])</td>
<td></td>
</tr>
<tr>
<td>MET 4</td>
<td>3.30 4.00 3.40 3.60</td>
<td></td>
</tr>
<tr>
<td>Ring zone diameter, D ([\text{mm}])</td>
<td>4.60 5.60 4.20 4.40</td>
<td></td>
</tr>
<tr>
<td>Ring zone width, B ([\text{mm}])</td>
<td>15.00 14.86 14.79 14.82</td>
<td></td>
</tr>
<tr>
<td>Adherence ([\text{N/mm}^2])</td>
<td>17.54 21.42 18.48 19.50</td>
<td></td>
</tr>
<tr>
<td>Inox 18-8</td>
<td>Force, when failing, F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>([\times 10^4 N])</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.20 5.20 4.50 4.80</td>
<td></td>
</tr>
<tr>
<td>Ring zone diameter, D ([\text{mm}])</td>
<td>4.00 39.68 39.40 39.42</td>
<td></td>
</tr>
<tr>
<td>Ring zone width, B ([\text{mm}])</td>
<td>14.99 14.83 14.76 14.98</td>
<td></td>
</tr>
<tr>
<td>Adherence ([\text{N/mm}^2])</td>
<td>22.31 28.14 24.64 25.89</td>
<td></td>
</tr>
<tr>
<td>S12Mn2Si</td>
<td>Force, when failing, F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>([\times 10^4 N])</td>
<td></td>
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<td>Adherence ([\text{N/mm}^2])</td>
<td>22.31 28.14 24.64 25.89</td>
<td></td>
</tr>
<tr>
<td>Al-Oi</td>
<td>Force, when failing, F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>([\times 10^4 N])</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.20 5.20 4.50 4.80</td>
<td></td>
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<tr>
<td>Ring zone diameter, D ([\text{mm}])</td>
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<td>Adherence ([\text{N/mm}^2])</td>
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<td></td>
</tr>
</tbody>
</table>
Figure 7 shows the curves, when there is no cracking of the sprayed coating, only its failing after plastic yielding. The other possible situation, is that presented in figure 8, when, at some moment, the coating cracks and so, falls off the basic substrate.

The graph of force variation as function of coating’s displacement is evidenced by figure 9.

As noticed, from the obtained results, the machining parameters do, hardly, affect metallized coating’s adherence. Usually, its values are a little higher, than the initial ones (without machining) maybe, because of the internal stresses that do appear while turning.

The experimental results of thermal sprayed coatings adherence study, induced the idea of finding a regression model, involving adherence values (as dependent variable) and machining parameters value (as independent variables) [5].

As, there have been noticed two types of force and displacement variation graphs, one for so called “mild materials” and the other for “hard materials”, detailed study was carried on the two opposite materials – compared to their hardness values, meaning Al-OI and, respectively, MET 4.

The experiments designs were full factorial ones and all of the regression analysis was performed with a special software, called DOE KISS. This software enables the study of each factor’s influence, as well as the factors’ interaction influence on the considered variable [7].

It’s worth to be mentioned that one factor, or interaction, is considered to have significant influence on the “output” if, the corresponding value of P (2 tail) is smaller than 0.05 – see figure 10 (for MET 4) and figure 11 (for Al-OI).
So, considering only the significant factors, the obtained regression models were:

- for MET4 metallized coating

\[ Y = 20.088 - 1.1425x_3 + 0.3175x_1 \cdot x_3 \]  

(1)

where: \( Y \) is the adherence variable [N/mm²];

\[ x_1 = \frac{v - v_{\text{min}} + v_{\text{max}}}{2} \]
\[ x_2 = \frac{v_{\text{max}} - v_{\text{min}}}{20} \]
\[ x_3 = \frac{t - t_{\text{min}} + t_{\text{max}}}{2} \]
\[ x_4 = \frac{t_{\text{max}} - t_{\text{min}}}{0.45} \]

resulting:

\[ Y \approx 25.421 - 3.383t - 0.096v + 0.218vt \]  

(2)

- for Al-OI metallized coating

\[ Y = 21.446 - 0.79875x_3 \]  

(3)

where: \( Y \) is the adherence variable [N/mm²];

\[ x_3 = \frac{t - t_{\text{min}} + t_{\text{max}}}{2} \]
\[ x_4 = \frac{t_{\text{max}} - t_{\text{min}}}{0.15} \]

resulting:

\[ Y \approx 23.842 - 10.65t \]  

(4)

4 Conclusion

Thermal sprayed coatings represent completely new materials (compared to the rough, initial ones) with very good mechanical characteristics – hardness, porosity, adherence, etc.

Many times, after metallizing, machining of the obtained coatings is necessary and, one important procedure is that of turning. For studying machining parameters influence on sprayed coating adherence there have been designed and manufactured special elements. All the experiments were carried out according to standardized conditions.

With two transducers type (fixed on the special elements) – a resistive and an inductive one, together with a data acquisition system, it was possible to plot the graphs of force (applied on the experimental samples) and displacement (of the tested metallized coating) variation. For “hard” materials, there was a “crack” of the coating while, for the “mild” materials, the coating just “slipped” down, with no sudden force variation.

As presented, it was the cutting depth, \( t \), parameter that did influence (but, not so high) the coating’s adherence, after its machining. Another factor with significant influence was, the interaction between cutting speed and cutting depth but, only for “hard” materials case.

Further research should be developed, in order to find if, there are any, more factors that could, possible, reduce or, even increase, studied adherence

References:


Fig. 11 Regression analysis results, with DOE KISS – for AI-OI thermal sprayed coating

So, considering only the significant factors, the obtained regression models were:

- for MET4 metallized coating

\[ Y = 20.088 - 1.1425x_3 + 0.3175x_1 \cdot x_3 \]  

(1)

where: \( Y \) is the adherence variable [N/mm²];

\[ x_1 = \frac{v - v_{\text{min}} + v_{\text{max}}}{2} \]
\[ x_2 = \frac{v_{\text{max}} - v_{\text{min}}}{20} \]
\[ x_3 = \frac{t - t_{\text{min}} + t_{\text{max}}}{2} \]
\[ x_4 = \frac{t_{\text{max}} - t_{\text{min}}}{0.45} \]

resulting:

\[ Y \approx 25.421 - 3.383t - 0.096v + 0.218vt \]  

(2)