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DEA RANKING THE GRINDABILITY OF STEELS

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Abstract: The paper presents the possibility for using a management analysis tool, namely Data Envelopment Analysis (DEA) for ranking the efficiency of grinding common heat treated steels used in machine building. The proposed technique proved to be able, to discriminate between seven steel grades and rank them through efficiency scores in order to rank their ability to be ground.

Key words: grinding, grindability, DEA, data envelopment analysis

1. INTRODUCTION

This article will examine grindability characteristics for some common steel grades and rank their capacity to be ground by using data envelopment analysis – DEA. Grindability is a general concept meaning different things to different people. To some specialists it implies the relative ease by which the stock can be removed from the surface of the workpiece material. To others it refers to the ability of the material to be ground at high rates of removal without making grinding burns or introducing residual stresses or other phenomena affecting the surface quality and further function of the part. Grindability can be qualitatively assessed (e.g. steel A grinds more easily than steel B), or quantitatively assessed using numerical index of some kind. Quantitative assessments require measurement of material removal under well specified and controlled grinding conditions. Because there are many kinds of grinding it is possible that any particular measure of material grindability may not correlate in the same way to all grinding processes. Obviously, the closer the grindability test conditions approach the actual grinding process, the assessment of quantitative grindability test will be more accurate. The proposed procedure (Julean, 2007) try to rely on the basic abrasive process: namely an abrasive surface (grinding wheel surface) moving towards the analyzed steel surface in controlled conditions (constant normal force). Therefore the significance of some specific material properties specific to hardened steels e.g. carbon content, chromium and vanadium content, HRC hardness and ultimate tensile strength R and others specific to the method of assessing the grindability p_{crit} and slope k, not considered usually when grinding process is done, were considered as inputs and outputs in the analysis.

2. DEA ANALYSIS

Data envelopment analysis (DEA) has become an important tool for the comparisons of set of peer entities called decision making units (DMUs) which convert multiple inputs into multiple outputs, in terms of efficiency and has been applied to many fields for evaluating and improving the performance of manufacturing and service operations. It has been extensively applied in performance evaluation and benchmarking of schools, hospitals, bank branches, production plants, etc. (Charnes et al., 1978). Its advantages are well known. Any number of inputs and outputs can be included in the analysis and no specific functional form of their relationships is assumed. This was the reason for choosing such a tool for ranking the performance in grinding different steel grades due the fact that there is not available any analytical model to link material properties and grindability of steels, yet.

DEA is a multi-factor productivity analysis model for measuring the relative efficiencies of a homogenous set of decision making units (DMUs). The efficiency score in the presence of multiple input and output factors is defined as:

\[
\text{Efficiency} = \frac{\text{weighted sum of outputs}}{\text{weighted sum of inputs}}
\] (1)

This definition requires a set of weights to be defined. This problem can be resolved by arguing that individual units may have their own particular value systems and therefore may legitimate define their own peculiar set of weights.
We assume that there are $n$ DMUs to be evaluated. Each DMU consumes varying amounts of $m$ different inputs to produce $s$ different outputs. Specifically, DMU $i$ consumes amount $x_{ij}$ of input $i$ and produces amount $y_{ik}$ of output $k$. We assume that $x_{ij} \leq 0$ and $y_{ik} \leq 0$ and further assume that each DMU has at least one positive input and one positive output value. The relative efficiency score of a test DMU is obtained by solving the following CCR model (Charnes, Cooper, and Rhodes, 1978):

$$\begin{align*}
\max & \sum_{i=1}^{n} v_i y_{ip} \\
\text{subject to} & \sum_{k=1}^{s} v_k y_{kp} \\& \sum_{j=1}^{m} u_j x_{jp} \leq 1 \forall i \\& \sum_{k=1}^{s} u_k x_{kj} = 1 \\& v_k, u_j \geq 0 \forall k, j
\end{align*}$$

where $k = 1$ to $s$, $j = 1$ to $m$, $i = 1$ to $n$, $y_k$ = amount of output $k$ produced by DMU $i$, $x_j$ = amount of input $j$ utilized by DMU $i$, $v_i$ = weight given to output $k$, $u_j$ = weight given to input $j$.

By using asset of normalizing constraints the fractional program (2) can be converted to a linear program (3), known as by multiple form of a linear programming problem DEA:

$$\begin{align*}
\max & \sum_{i=1}^{n} v_i y_{ip} \\
\text{subject to} & \sum_{j=1}^{m} u_j x_{jp} = 1 \\& \sum_{k=1}^{s} v_k y_{kp} - \sum_{j=1}^{m} u_j x_{kj} \leq 0 \forall i \\& v_k, u_j \geq 0 \forall k, j
\end{align*}$$

The problem is run $n$ times in identifying the relative efficiency scores of all the DMUs. Each DMU selects input and output weights that maximize its efficiency score. In general, a DMU is considered to be efficient if it obtains a score of $1$ and a score of less than $1$ implies that it is inefficient. Using duality from linear programming the dual form problem (4) may be obtained:

$$\begin{align*}
\min & \theta \\
\text{subjected to} & \sum_{i=1}^{n} \lambda_i x_{ip} - \theta x_{jp} \leq 0 \forall j \\& \sum_{j=1}^{m} \lambda_j y_{ij} - y_{jp} \geq 0 \forall k \\
& \lambda_i \geq 0 \forall i
\end{align*}$$

where $\theta$ is the efficiency score and $\lambda$ is the vector of the dual variables.

According to DEA technique the efficiency scores $\theta \in (0, 1]$. If we consider the DMUs as the steel grades then the higher $\theta$ score will mean better grindability.

3. GRINDABILITY TESTING METHOD

Usual the grindability is considered in terms of removal rate, cost, and quality of ground surface. The cost effective machining of steels requires that assessing the grindability should be easy to obtain experimentally. Volumetric removal rate under controlled-force grinding is a cost effective measure for steels grindability. In grinding, the material removal rate $Q$ is a function of many variables as: wheel speed, normal grinding force, material properties, and wheel characteristics. Under constant grinding force $F_n$ and constant wheel speed $v_w$, the material removing rate $Q$ remains as a function of the normal grinding force $F_n$, material properties $M_p$ and grinding wheel characteristics $W_o$ or:

$$Z = f(F_n, M_p, W_o)$$

Experimental results indicate that a proportional relationship exists between material removal rate and the normal grinding force $F_n$. Therefore, a grindability index $I_g$ can be defined as:

$$I_g \propto \frac{Z}{F_n}$$

Using the instant contact area between the wheel and the workpiece, $A$, equation (2) becomes:

$$I_g \propto \frac{\partial Z}{\partial A}$$

where: $\partial Z/\partial A$ represents the infeed rate and $p$ the contact pressure between the grinding wheel and workpiece surface.

Figure 1 and figure 2 present the experimental setup for assessing the steels grindability. During the grinding process, the test specimen is grind with constant normal force $F_n$. Due the action of
a weight $G$ placed at the end of a balanced lever. The vertical displacement of the test specimen was measured with an electronic gauge. The signal is processed with a Flytech ADDA 14 card and a PC computer.

The cylindrical test specimen ($\Phi=10$ mm) exposes to the grinding wheel active surface a conical surface with a 120° apex angle. During grinding with the constant normal force $F_n$, the wheel test specimen contact area is continuously increased and consequently the contact pressure decreased and the infeed ratio too.

![Fig. 1. Schematic diagram of the experimental setup](image1)

![Fig. 2. View of the experimental setup](image2)

For assessing the grindability, two variables have been taken in account: the infeed rate and the contact pressure $p$, between the wheel and the test specimen. Using the linear regression the dependence between the infeed rate and the contact pressure had been calculated. The value of critical pressure $p_{crit}$ corresponding to the moment when infeed rate becomes null and when practically the grinding is turned into rubbing, has been achieved. So $p_{crit}$ is the intersection of the regression line with the pressure axis (fig. 3). Analyzing the experimental results, significant differences has been found between the regression line slopes $k$ for different steel grades. It was found that grindability could be connected with the slope $k$ and critical pressure $p_{crit}$. If a particular steel grade will produce, during the tests, a high slope $k$, and a lower $p_{crit}$ then it will be easy to grind. When the grindability is assessed for different steels it is important to keep the same grinding conditions so the wheel surface must be fresh dressed for each test. The wheel specifications will meet the usual recommendation for the family of steels tested.

![Fig. 3: Infeed rate versus pressure for 205Cr115 steel](image3)

**4. DATA PROCESSING AND ANALYSIS**

Due the fact that in grinding, deformation, ploughing, cutting, friction, and fracture are involved, grindability may be regarded as connected with mechanical properties of the steels like: hardness, ultimate tensile strength, fracture toughness, flexural strength etc. It is difficult to achieve an analytical model to connect all material technological properties with grindability. The ease of grinding after heat treatment is usually inversely proportional to the base hardness, the volume of carbide phase present, and the hardness of individual carbide particles. Steels containing higher percentages of carbon and carbide-forming alloying elements are difficult to grind. Steels relative high in carbide forming elements are more difficult to grind then the carbon or law-alloy types, even though hardness and carbon content may be higher for the law-alloy steels, (Davis, 1995). Grindability of steel decreases as hardness increase. However, the magnitude of the difference contributed by hardness varies considerably with different compositions (Malkin, 1989)., (Marinescu, et al. 2006).
Table 1: Steel grades parameters used for evaluation of grindability with DEA

<table>
<thead>
<tr>
<th>DMUs</th>
<th>Steel grade</th>
<th>Equivalences with DIN</th>
<th>Input parameters</th>
<th>Output parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C%</td>
<td>Cr%</td>
</tr>
<tr>
<td>n=1</td>
<td>OLC 15</td>
<td>1.1141</td>
<td>0.15</td>
<td>0</td>
</tr>
<tr>
<td>n=2</td>
<td>OLC45</td>
<td>1.1191</td>
<td>0.45</td>
<td>0</td>
</tr>
<tr>
<td>n=3</td>
<td>16MnCr5</td>
<td>1.7131</td>
<td>0.17</td>
<td>0.95</td>
</tr>
<tr>
<td>n=4</td>
<td>42CrMo4</td>
<td>1.7225</td>
<td>0.41</td>
<td>1.05</td>
</tr>
<tr>
<td>n=5</td>
<td>100Cr7</td>
<td>1.2067</td>
<td>1</td>
<td>1.45</td>
</tr>
<tr>
<td>n=6</td>
<td>X205Cr115</td>
<td>1.208</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>n=7</td>
<td>OSC8</td>
<td>1.1525</td>
<td>0.85</td>
<td>0</td>
</tr>
</tbody>
</table>

Following the DEA procedure, 7 steel grades were identified as seven DMUs. For each DMU the input parameters were: C% content, Cr% content, ultimate tensile strength R, and HRC hardness after specific heat treatment. The output parameters were $P_{crit}$ and k, obtained after processing data acquired from the grindability tests. Critical pressure $P_{crit}$ increasing is negatively influencing the grindability and whereas slope k increasing is meaning an ease in grinding, so the reciprocal values were used in the analysis. Using the procedure described in paragraph 2 and the programming model (4), 7 different efficiency scores $\theta$ were obtained and displayed graphically in figure 4. One can observe that the best score ($\theta=1$) was obtained in the case of case hardened steel OLC15, meanwhile the smallest in case of high chromium steel X205Cr115 ($\theta=0.7687$).

Fig. 4: Ranking steel grades by efficiency scores (grindability) obtained via DEA analysis

The $\theta$ scores are ranking the grindability of the analyzed steels in agreement with the known factors of influence as C content, carbide content, hardness, etc. The highest grindability obtained in case of OLC 15 and 16MnCr5 could be explained by weakest mechanical properties and by probably an inconsistent hardened layer on the apex of the testing specimens.

5. CONCLUSIONS

DEA analysis proved to be a powerful tool in classifying grindability of different steel grades frequently involved in machine manufacturing. Without any functional defined relationship between some mechanical properties and the results of grinding process, in terms G-ratio, grinding force or roughness, the ranking of the ability to be ground of the seven steel grades involved in experiments was obtained using a simple experimental procedure by using DEA. The strong influence of carbon and chromium content on grindability was confirmed.

6. REFERENCES