Polar machinability diagrams - a model to predict the machinability of a work material

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POLAR MACHINABILITY DIAGRAMS – A MODEL TO PREDICT THE MACHINABILITY OF A WORK MATERIAL

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Abstract: The article presents a newly developed model for the description and classification of machinability, based on comparison with a reference material. The model illustrates critical machinability properties in a polar diagram with 5 axes and poles. Each axis represents a behaviour or property, i.e. abrasiveness or hardness. The total machinability profile of a work material can then be outlined by grading the 5 different machinability properties. The polar diagram can be correlated to the corresponding tool properties and the cutting data suitable for the material and the process.

Keywords: Metal cutting, machinability, work materials.

1. BACKGROUND

Machinability is a concept within metal cutting that has been used for a long time. In its simplest definition the term describes ”how easily a work material can be machined with a cutting tool, given prescribed tolerances regarding form, dimension and surface”. A supplement that is immediately obvious to add is that this has to be done in regard to the key parameters part quality, process interference and production pace (productivity). Consequently, machinability becomes a complex factor that rather describes the process outturn, than specific workpiece properties.

It is then common to divide the machinability concept into the parameters; cutting forces, chip forming, surface integrity, tool wear and environmental factors. Which of these that has the highest weight and importance may vary during the machining of a part, some parameters are critical during roughing and some are more critical during finishing.

Apart from the complexity of the machinability concept, there is a need to be able to generalize and compare machinability in a rational and effective way. Set-up costs associated with the introduction of new or unknown work materials can be reduced if it’s possible to accurately predict the machinability of a material.

2. THE POLAR MACHINABILITY DIAGRAM

Within the SSF financed ProViking project Shortcut, models and methods are developed in order to achieve more effective and faster technology shifts for metal cutting operations. The presented model outlines and describes how a work material acts during metal cutting, by adopting the general material properties and evaluate their impact on machinability. The 5 different characteristic properties that forms the model (abrasiveness, adhesion, strain hardening, hardness and thermal conductivity) describes the essential material related properties that has an impact on process stability and tool wear during metal cutting. The fundamental idea with the model is that the process behaviour in metal cutting operations, of a given material, should be understood only by studying the polar machinability diagram. Further on, a comprehensive view of the process is created when changes in tool properties and process parameters can be connected to the character of the polar diagram. To be able to draw the right conclusions from this, it is necessary to posses basic knowledge of the different characteristic material properties, tool properties and the process

parameters, this is accounted for later on in this work.
By studying the diagrams, it should also be possible to better understand which tool material that matches a certain work material. It should be noted that work materials are generally classified into groups, where a certain property governs this classification. More often, a work material can't be classified just to one group; this is especially valid for the difficult to machine materials.
A typical example of this is the duplex stainless steels, e.g. SS2377 a ferritic austenitic stainless steel that exhibits two different characteristic properties. This material exhibits the adhesive properties from the ferrite structure and the strain hardening properties of the austenitic phase. This makes the material difficult to classify, whereupon the description of it would be more obvious if more properties were represented.
Another example is high-alloy stainless steels, which are strain hardening at the same time as the thermal conductivity is low. Based upon cases and discussions like this, the new model for complex machinability classification is suggested.
The model is based on a polar diagram with 5 axes. The different axes represent each of the presented characteristic material properties. The axes are graduated in 10 levels, where the value 10 means that the material exhibits extreme behaviour related to the specific property. Figure 1 shows the concept of the polar diagram for a fictive material.

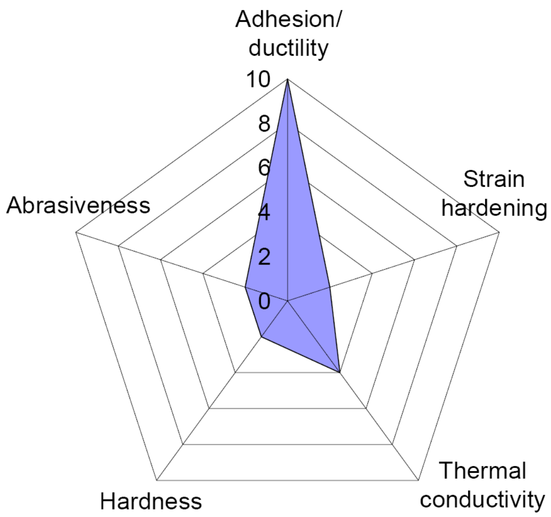

Figure 1. Illustration of a polar machinability diagram for a highly adhesive material.

3. THE 5 POLES

As mentioned before, a certain basic knowledge is needed to be able to interpret the diagram. The following short descriptions provide the general features of the 5 different characteristic properties. The descriptions are formulated as discussions around materials with that distinct property.

Abrasive materials
Abrasive materials are characterized by the relatively high contents of abrasive and wearing particles in the original metal. The particles are often very hard carbides or oxides, which causes an abrasive wear on the cutting tool.

Adhesive materials
The adhesion or bonding between work material and cutting tool (and its coatings) is one of the behaviours that makes the cutting process very complex and many times hard to predict. By experience, highly adhesive materials are also tuogh and ductile materials, with a high break elongation. Adhesion can be a big machinability problem, but in some cases it can sometimes also be an advantage. If the strength ot the bond between tool and work material is strong enough, the tool will be protected from wear and therefore get a long tool life. If the bond is weaker and the built up material is deposited discontiously, a very progressiv and rapid wear can be obtained. The difference between these two cases can be very small. Only very small differences in material properties can have a dramatic impact on the functionality of the cutting process.

Strain hardening materials
Strain hardening of a work material influences the chip properties, among other things. A strain hardening material will cause a relatively large variation of properties in the machined material. The cut surface layer will have a much higher hardness than the undeformed material. The increased hardness of the cut surface layer results in a increased edge load if h_1 is chosen lower than the thickness of the deformed layer, making higher feed an obvoius choice when finish machining these materials. The geometry of the cutting edge becomes specially important in these applications. Strain hardening in combination with a low thermal conductivity results in a relatively poor machinalility, as for example austenitic stainless steels.

Materials with low thermal conductivity
Significant for a material with low thermal conductivity is the problem with heat transport in the cutting process. This is revealed by the increase of process temperatures and the often occurring plastic deformation of the cutting tool, if the temperature progress is not controlled.

Hard materials
An increased deformation resistance often leads to higher cutting forces and by that a higher cutting

resistance. The hardness of a material is usually directly correlated to the materials deformation resistance and cutting resistance. Hardness variations are often correlated to structural distrubution of the material. A material with varying hardness can be expected to generate varying cutting forces. The material will produce short chips or segmented chips.

4. TOOL SELECTION SUPPORTED BY POLAR MACHINABILITY DIAGRAMS

Figure 2 shows how the selection of cutting tools can be correlated to the polar machinability diagram. The figure should be interpreted as follows; the more polarized properties a material shows, for example adhesiveness, the higher are the demands on the tool to meet this effect.

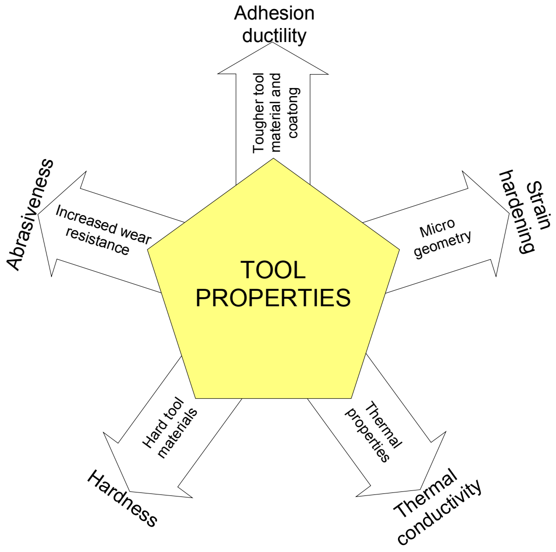

Figure 2. The interaction between the polar diagram and the tool properties.

Increased wear resistance (abrasiveness)
The correlation between the work materials abrasive properties and the tool properties can be identified as the tools resistance to deterioration through loss of material. The direct connection is the hardness of the tool material, that is the more abrasive the work material is, the harder the tool material should be. Since diamond and CBN both are superhard tool materials, these are often used in applications with abrasive work materials. The overall governing process parameter is otherwise is the temperature. For less abrasive materials it could be advisable to chose carbide inserts with a thick layer of Al_2O_3.

Tougher tool material and coating material (adhesiveness)
Work materials with an adhesive behaviour calls for a tougher tool material adapted for this type of load. The choice of tool material is therefore often carbide tools that has a sufficient toughness.
The tools are usually coated with a low friction layer, for example TiN or diamond. PVD coatings are preferred, since this method induces less thermal residual stresses between coating and the base material, than the CVD method does. Generally, the coating is also thinner. This results in less micro chipping of the tool after PVD coating. The PVD coating has a stronger bond to the cemented carbide and do not get pulled off when the work material adheres to the tool. The tool life increases due to the reduction of wear induced by BUE.

Micro geometry (strain hardening)
Strain hardening of the work material can be met by adapting the tool geometry. This can be done using two very diverging strategies, either minimizing the load or maximizing the tool strength. Maximizing the tool strength means that the cutting edge has a relatively large protective edge chamfer. This leads to relatively large cutting forces, but also to a tool that can better balance these forces. A positive rake angle and relief angle produces the opposite, a tool that cuts more easily through strain hardened layers, but also a tool with less load capacity.

Thermal properties (poor thermal conductivity)
A tool material that can resist high process temperatures without plastic deformation is desired. The too should also be able to withstand the diffusion which is driven by temperature.

Hard tool materials (hardness)
Generally it can be stated that a hard work material must be met with a hard tool material. There is however other important tool parameters, such as tool geometry. The tool geometry must balance the high cutting resistance. Up to a certain h1 limit, the compressive strength of the tool is the decisive load case. The compressive strength (σ_{CS}) in most cases is directly correlated to the tool materials hardness and abrasive wear resistance. On the other hand, an increased h_1 requires increased levels of the ultimate flexural strength (σ_{FS}) of the tool material, which physically gives a lower compressive strength and wear resistance.

THE CORRELATION BETWEEN CUTTING DATA AND THE POLAR MACHINABILITY DIAGRAM

Figure 3 illustrates the correlation between cutting data and the polar machinability diagram.

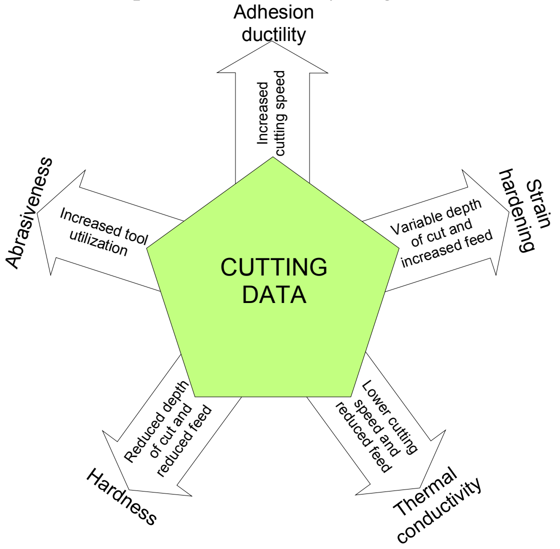

Figure 3. The interaction between the polar diagram and the tool properties.

<u>Increased tool utilization (abrasiveness)</u>
A pure abrasive behaviour is independent of cutting data and other process parameters. The tool is worn proportional to the length of tool engagement. The only thing that can increase the tool life, is to better utilize the cutting tool, by distributing the wear on a larger tool area. This can practically be achieved by varying the depth-of-cut and possibly the feed.

<u>Increased cutting speed (adhesiveness)</u>
Problems with built-up edges and adhesion can be avoided by increasing the cutting speed, if the process allows for this. Adhesion can also be decreasing by applying cutting fluids, specifically in processes with large contact areas and relatively low contact pressures. The use of cutting fluids can some time cool the process down to the BUE region, which demands for an increase of cutting speed.

<u>Variable depth-of-cut and increased feed (strain hardening)</u>
For a strain hardening material, the cutting should be performed under the deformed layer. This is practice executed by avoiding small feeds. The theoretical chip thickness h1 must be larger than the thickness of the deformed zone under the tool flank. It is possible also, to use a variable depth-of cut, to distribute the tool wear more evenly.

<u>Lower cutting speed and reduced feed (poor thermal conductivity)</u>
The influence of poor thermal conductivity can be reduced by lowering the process temperature. This can be achieved by lowering the feed or the cutting speed.

<u>Reduced depth-of-cut and reduced feed (hardness)</u>
When machining hard materials it is common to reduce the feed and depth-of-cut, in order to reduce the mechanical load on the tool edge.

5. POLAR MACHINABILITY DIAGRAMS FOR SELECTED MATERIALS

The following diagrams show an attempt to estimate and classify the machinability of some selected materials, using the suggested polar charts. A reference material is needed, in order to make use of the 10 grade scales. The reference material was chosen to be SS 2244. The reference material is given the value 5 on all axes in the polar diagram and all other materials are graded relative to this. It is important to notice that the diagrams exemplify a general behaviour of the material. A polar diagram is also only valid for one specific condition of the material, if the condition is changed a new polar diagram has to be set up.

Figure 4 shows the polar machinability diagram for SS2244. This material is a low alloy steel with ca 0.45% C. The material can be heat treated and is used for various construction parts.

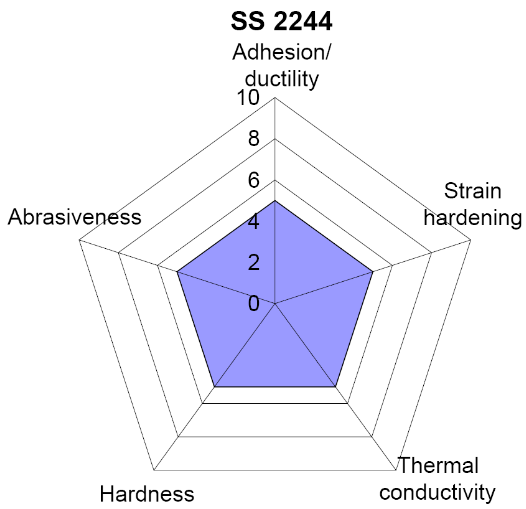

Figure 4. Machinability diagram for the reference material SS 2244.

The material SS 2377 is illustrated in Figure 5 SS2377 is a duplex stainless steel, meaning that it has a ferrite-austenitic microstructure. In SS the ferrite content is 40-60%. Since the material contains two different structures it will display characteristics from both. During machining, the material will show adhesion (due to the ferrite phase) and show strain hardening (due to the austenitic phase). The thermal conductivity is relatively poor, due to the high alloy content.

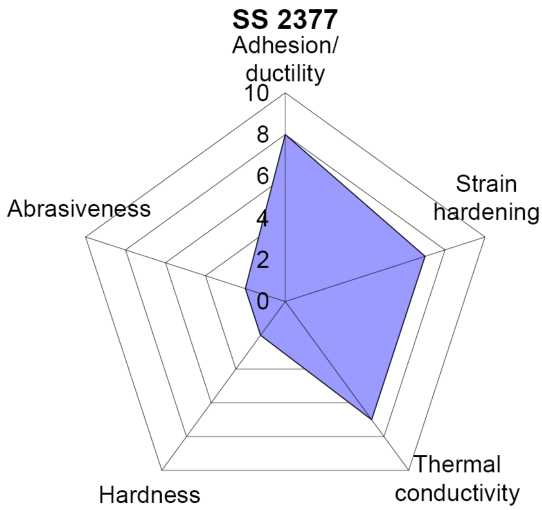

Figure 5. Polar machinability diagram for the work material SS 2377.

Inconel 718 is a nickel based super alloy. The material combines qualities like high corrosion resistance, high strength and weldability. The material has excellent creep properties up to 700°C.

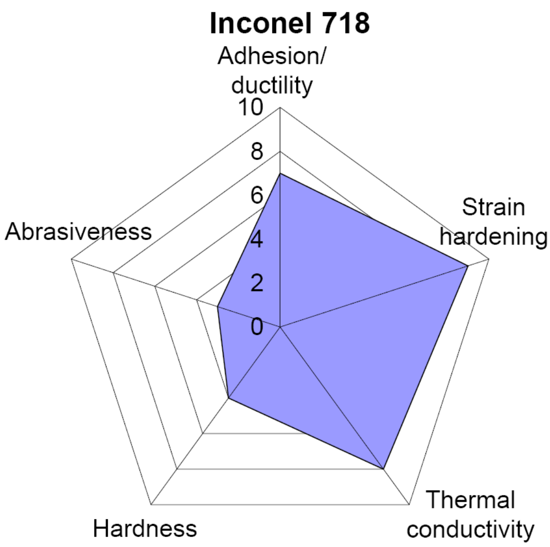

Figure 6. Polar machinability diagram for the work material Inconel 718.

The polar machinability diagram is presented in Figure 6. During machining, Inconel 718 displays a distinct strain hardening behaviour. It is relatively adhesive and has a poor thermal conductivity.

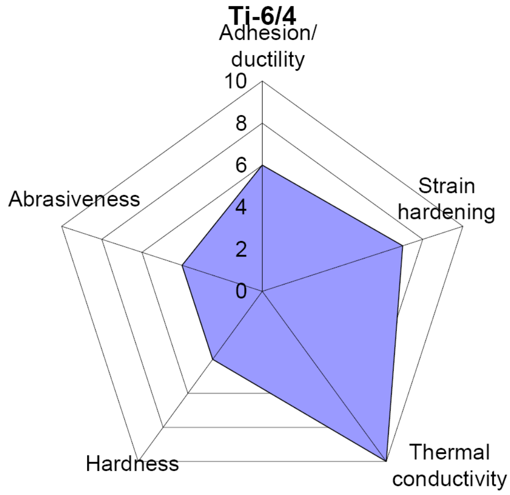

Figure 7. Polar machinability diagram for the work material Ti-6/4.

Titanium 6/4 was one of the early titanium alloys, but is still used widely. This is mainly due to the flexibility in production alternatives; it is both superplastic and can be cast. The alloy is a α+β-alloy, i.e. both α- och β-phase are present in the material. Figure 7 shows the Ti 6/4 diagram. Characteristic features are poor thermal conductivity and some strain hardening.

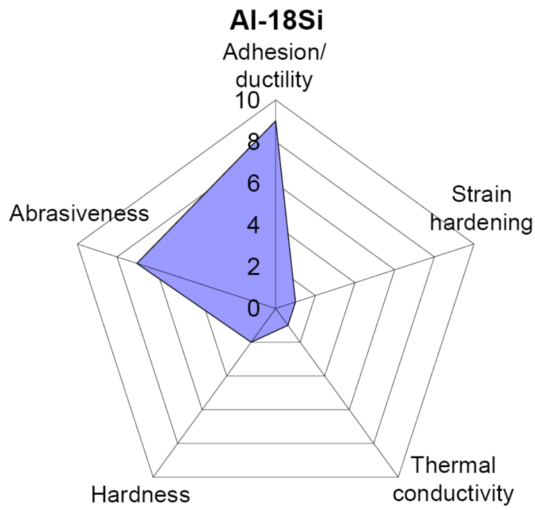

Figure 8. Polar machinability diagram for the work material Al-18Si.

Al-18 is a casting alloy with 18% Si content. The material is hypereutectic which results in free silicon crystals, which in turn results in a heavy abrasive wear of the cutting tool, see Figure 8. The material has excellent thermal conductivity, significant for aluminium alloys.

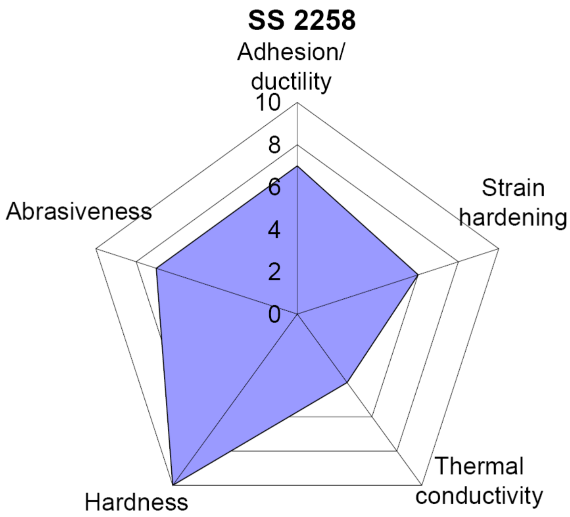

Figure 9. Polar machinability diagram for the work material SS 2258.

SS 2258 is a bearing steel. The high carbon content and the added chromium make the material hard and wear resistant. The machinability characteristics are shown in Figure 9. The material is hard and abrasive, but also shows some adhesiveness. The thermal conductivity is fairly good.

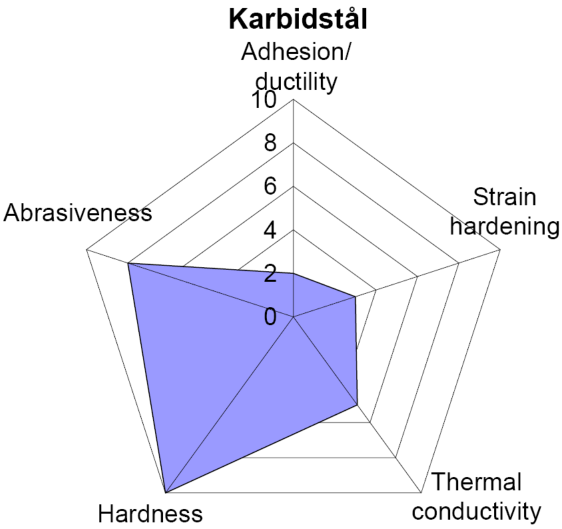

Figure 10. Polar machinability diagram for the work material Karbidstål.

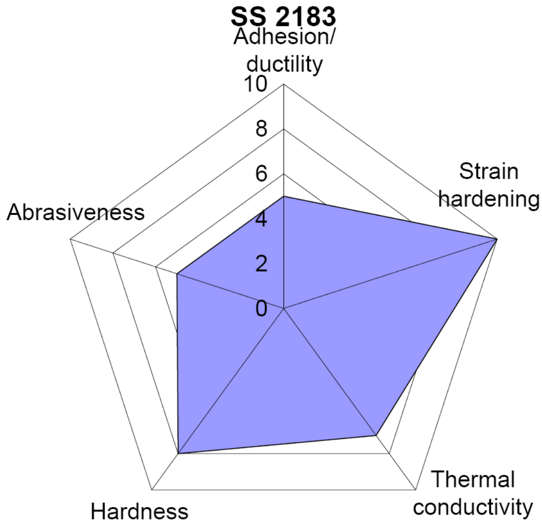

Figure 11. Polar machinability diagram for the work material SS 2183.

Carbide steel or "Karbidstål" is a recently developed cast alloy. Fundamentally it's a white cast iron, but with a high content of chromium and cemented carbides as alloying members. The material is a casting alloy with a high hardness and an outstanding wear resistance. The machinability problems are related to the high hardness of the material, due to its micro structure and the high amount of carbides in the material, see Figure 10.

SS 2183 is a cast steel, or high-manganese steel. This steel has a high content of manganese and silicon, in order to enhance fluidity and the material ability to fill the casting moulds. The machinability of SS2183 is characterized by the heavy stain hardening, see Figure 11. The material is relatively hard and has a relatively poor thermal conductivity.

6. CONCLUSIONS

Since the presented model is based on critical machinability properties, work materials with similar polar chart profiles should display a similar behaviour in the cutting process. Therefore it should be possible to predict the machinability behaviour of an untested work material and it should also be possible to choose the appropriate tool properties and cutting data. The polar machinability diagram is built around factors and parameters that are difficult to measure. The diagram must therefore be filled in based on experience and know-how, and to a large degree on indirect data. Due to its nature, the polar diagram may be best suited to describe and predict the machinability of difficult to machine materials.

7. ACKNOWLEDGEMENTS

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