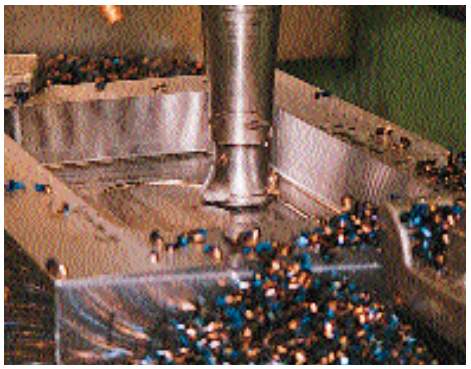
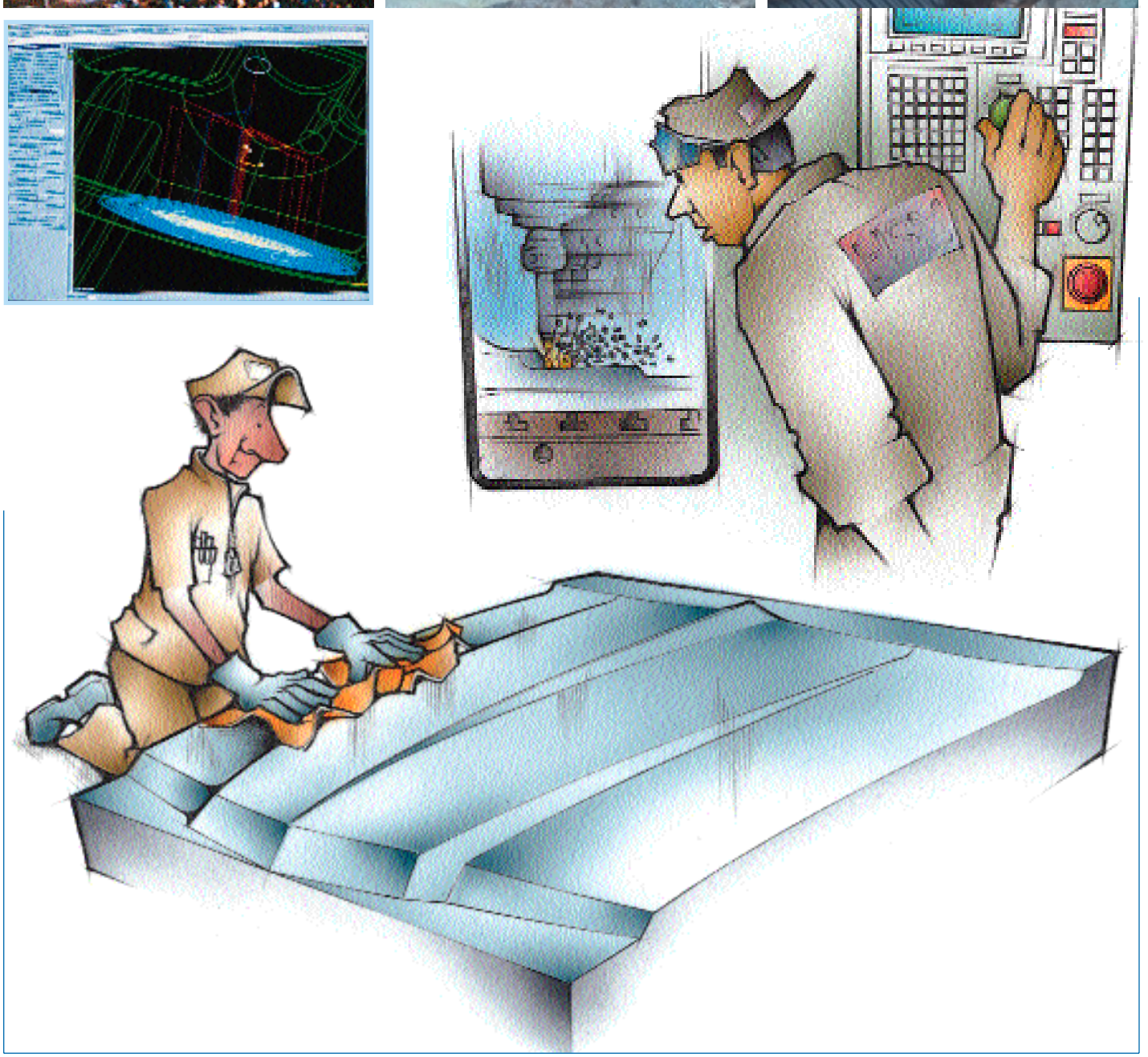
High speed machining and conventional die and mould machining





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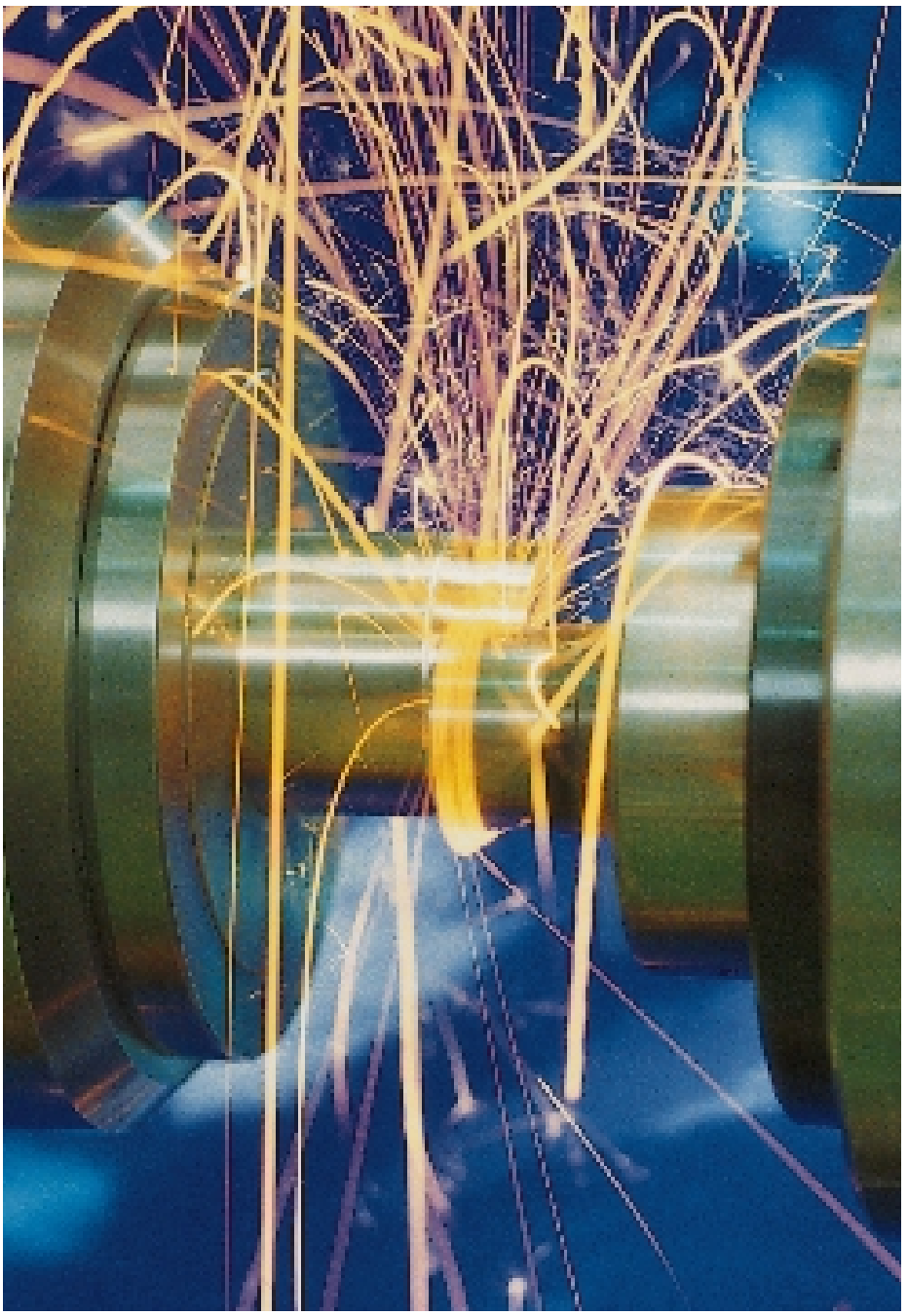
SANDVIK Coromant

HSM
- High Speed Machining

There are a lot of questions about HSM today and many different, more or less complicated, definitions can be seen frequently. Here the matter will be discussed in an easy fashion and from a practical point of view.

This article is the first in a series of articles about die and moldmaking from Sandvik Coromant. In a following article HSM will be further discussed.



Historical background

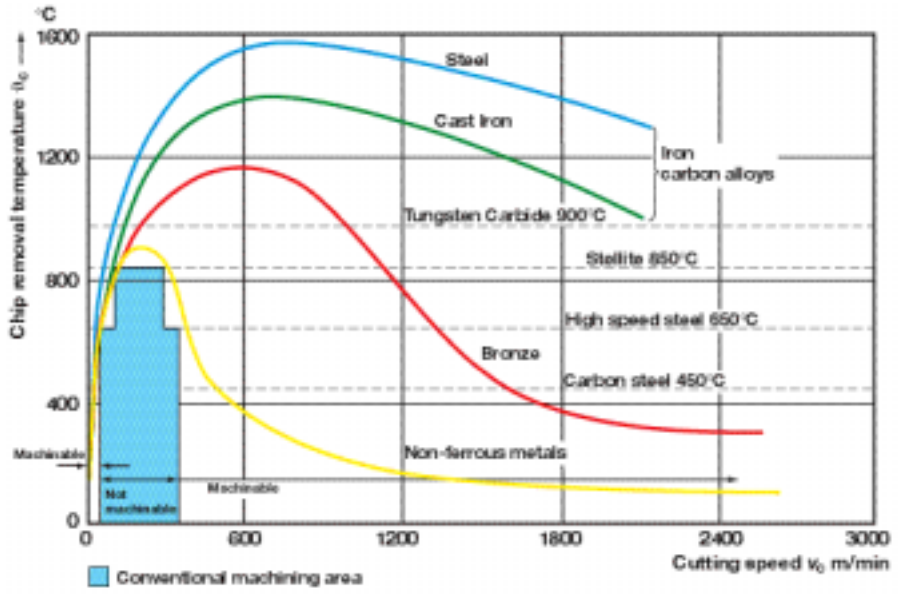
The term High Speed Machining (HSM) commonly refers to end milling at high rotational speeds and high surface feeds. For instance, the routing of pockets in aluminum airframe sections with a very high material removal rate. Over the past 60 years, HSM has been applied to a wide range of metallic and non-metallic workpiece materials, including the production of components with specific surface topography requirements and machining of materials with a hardness of 50 HRC and above. With most steel components hardened to approximately 32-42 HRC, machining options currently include:

- rough machining and semi-finishing of the material in its soft (annealed) condition
- heat treatment to achieve the final required hardness (</= 63 HRC)
- machining of electrodes and Electrical Discharge Machining (EDM) of specific parts of the dies or molds (specifically small radii and deep cavities with limited accessibility for metal cutting tools)
- finishing and super-finishing of cylindrical/flat/cavity surfaces with appropriate cemented carbide, cermet, solid carbide, mixed ceramic or polycrystalline cubic boron nitride (PCBN)

With many components, the production process involves a combination of these options and in the case of dies and molds it also includes time consuming hand finishing. Consequently, production costs can be high and lead times excessive.

Typical for the die and mold industry is to produce one or a few tools of the same design. The process includes constant changes of the design. And because of the need of design changes there is also a corresponding need of measuring and reverse engineering.

The main criteria is the quality of the die or mold regarding dimensional, geometrical and surface accuracy. If the quality level after machining is poor and if it can not meet the requirements there will be a varying need of manual finishing work. This work gives a satis-



Chip removal temperature as a result of the cutting speed.

fying surface accuracy, but it always has a negative impact on the dimensional and geometrical accuracy.

One of the main targets for the die and mold industry has been, and is, to reduce or eliminate the need of manual polishing and thus improve the quality, shorten the production costs and lead times.

Main economical and technical factors for the development of HSM

Survival - the ever increasing competition on the marketplace is setting new standards all the time. The demands on time and cost efficiency is getting higher and higher. This has forced the development of new processes and production techniques to take place. HSM provides hope and solutions...

Materials - the development of new, more difficult to machine materials has underlined the necessity to find new machining solutions. The aerospace industry has its heat resistant and stainless steel alloys. The automotive industry has different bimetal compositions, Compact Graphite Iron and an ever increasing volume of aluminum. The die and mold industry mainly has to face the problem to machine high hardened tool steels. From roughing to finishing.

Quality - the demand on higher component or product quality is a result of the hard competition. HSM offers, if applied correctly, solutions in this area. Substitution of manual finishing is one example. Especially important on dies or molds or components with a complex 3D geometry.

Processes - the demands on shorter through- put times via fewer set-ups and simplified flows (logistics) can be solved to a big extent via HSM. A typical target within the die and mold industry is to make a complete machining of fully hardened small sized tools in one set-up. Costly and time consuming EDM-processes can also be reduced or eliminated via HSM.

Design & development - one of the main tools in today's competition is to sell products on the value of novelty. The average product life cycle on cars is today 4 years, computers and accessories 1,5 years, hand phones 3 months... One of the prerequisites of this development of fast design changes and rapid product development time is the HSM technique.

Complex products - there is an increase of multifunctional surfaces on components. Such as new design of turbine blades giving new and optimised functions and features. Earlier design allowed polishing by hand or with robots (manipulators). The turbine blades with the new, more sophisticated design has to be finished via machining and preferably by HSM.

There are also more and more examples of thin walled workpieces that has to be machined (medical equipment, electronics, defence products, computer parts).

Production equipment - the strong development of cutting materials, holding tools, machine tools, controls and especially CAD/CAM features and equipment has opened possibilities that must be met with new production methods and techniques.

The original definition of HSM

Salomons theory, "Machining with high cutting speeds..." on which he got a German patent 1931, assumes that "at a certain cutting speed (5-10 times higher than in conventional machining), the chip removal temperature at the cutting edge will start to decrease...".

Giving the conclusion: ..."seem to give a chance to improve productivity in machining with conventional tools at high cutting speeds..."

Modern research has unfortunately not been able to verify this theory to its full extent. There is a relative decrease of the temperature at the cutting edge that starts at certain cutting speeds for different materials. The decrease is small for steel and cast iron. And bigger for aluminum and other non-ferrous metals. The definition of HSM must be based on other factors.

What is today's definition of HSM?

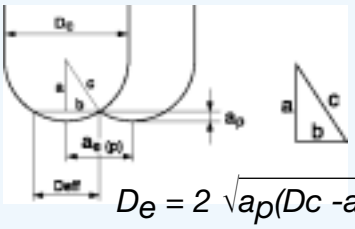
The discussion about high speed machining is to some extent characterised by confusion. There are many opinions, many myths and many different ways to define HSM. Looking upon a few of these definitions HSM is said to be:

- High Cutting Speed (v_c) Machining...
- High Spindle Speed (n) Machining...
- High Feed (v_f) Machining...
- High Speed and Feed Machining...
- High Productive Machining...

On following pages the parameters that influence the machining process and having connections with HSM will be discussed. It is important to describe HSM from a practical point of view and also give as many practical guidelines for the application of HSM as possible.

True cutting speed

As cutting speed is dependent on both spindle speed and the diameter of the tool, HSM should be defined as "true cutting speed" above a certain level. The linear dependence between cutting speed and feed rate results in "high feeds with high speeds". The feed will become even higher if a smaller cutter diameter is chosen, provided that the feed per tooth and the number of teeth is unchanged. To compensate for a smaller diameter the rpm must be increased to keep the same cutting speed...and the increased rpm gives a higher v_f.



$$D_e = 2\sqrt{a_p(D_c - a_p)}$$

Effective cutting speed (v_e)

$$v_e = \frac{\pi \times n \times D_e}{1000} \; m/min$$

$$V_f = f_z \times n \times z_n \quad [mm/min]$$

Formula for feed speed.

Shallow cuts

Very typical and necessary for HSM applications is that the depths of cut, a_e and a_p and the average chip thickness, h_m, are much lower compared with conventional machining. The material removal rate, Q, is consequently and considerably smaller than in conventional machining. With the exception when machining in aluminium, other non- ferrous materials and in finishing and superfinishing operations in all types of materials.

$$Q = \frac{a_p \times a_e \times v_f}{1000} \; [cm^3/min]$$

Formula for material removal rate.

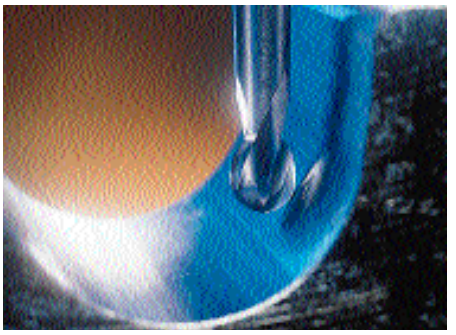
Application technology

To perform HSM applications it is necessary to use rigid and dedicated machine tools and controls with specific design features and options. All production equipment has to be designed for the specific process of HSM.

It is also necessary to use an advanced programming technique with the most favourable tool paths. The method to ensure constant stock for each operation and tool is a prerequisite for HSM and a basic criteria for high productivity and process security. Specific cutting and holding tools is also a must for this type of machining.

Characteristics of today's HSM in hardened tool steel

Within the die & mold area the maximum economical workpiece size for roughing to finishing with HSM is approximately 400 X 400 X 150 (l, w, h). The maximum size is related to the relatively low material removal rate in HSM. And of course also to the dynamics and size of the machine tool.



Most dies or moulds have a considerably smaller size, than mentioned above, in complete machining (single set-up). Typical operations performed are, roughing, semi-finishing, finishing and in many cases super-finishing. Restmilling of corners and radii should always be done to create constant stock for the following operation and tool. In many cases 3-4 tool types are used.

The common diameter range is from 1 - 20 mm. The cutting material is in 80 to 90% of the cases solid carbide end mills or ball nose end mills. End mills with big corner radii are often used. The solid carbide tools have reinforced cutting edges and neutral or negative rakes (mainly for materials above 54 HRC). One typical and important design feature is a thick core for maximum bending stiffness.

It is also favourable to use ball nose end mills with a short cutting edge and con-

tact length. Another design feature of importance is an undercutting capability, which is necessary when machining along steep walls with a small clearance. It is also possible to use smaller sized cutting tools with indexable inserts. Especially for roughing and semi-finishing. These should have maximum shank stability and bending stiffness. A tapered shank improves the rigidity. And so does also shanks made of heavy metal.

The geometry of the die or mold could preferably be shallow and not too complex. Some geometrical shapes are also more suited for high productive HSM. The more possibilities there are to adapt contouring tool paths in combination with downmilling, the better the result will be.

One main parameter to observe when finishing or super-finishing in hardened tool steel with HSM is to take shallow cuts. The depth of cut should not exceed 0,2/0,2 mm (a_e/a_p). This is to avoid excessive deflection of the holding/cutting tool and to keep a high tolerance level and geometrical accuracy on the machined die or mold. An evenly distributed stock for each tool will also guarantee a constant and high productivity. The cutting speed and feed rate will be on constant high levels when the a_e/a_p is constant. There will be less mechanical variations and work load on the cutting edge plus an improved tool life.

Cutting data

Typical cutting data for solid carbide end mills with a TiC,N or TiAlN-coating in hardened steel: 48-58 HRC.

Roughing

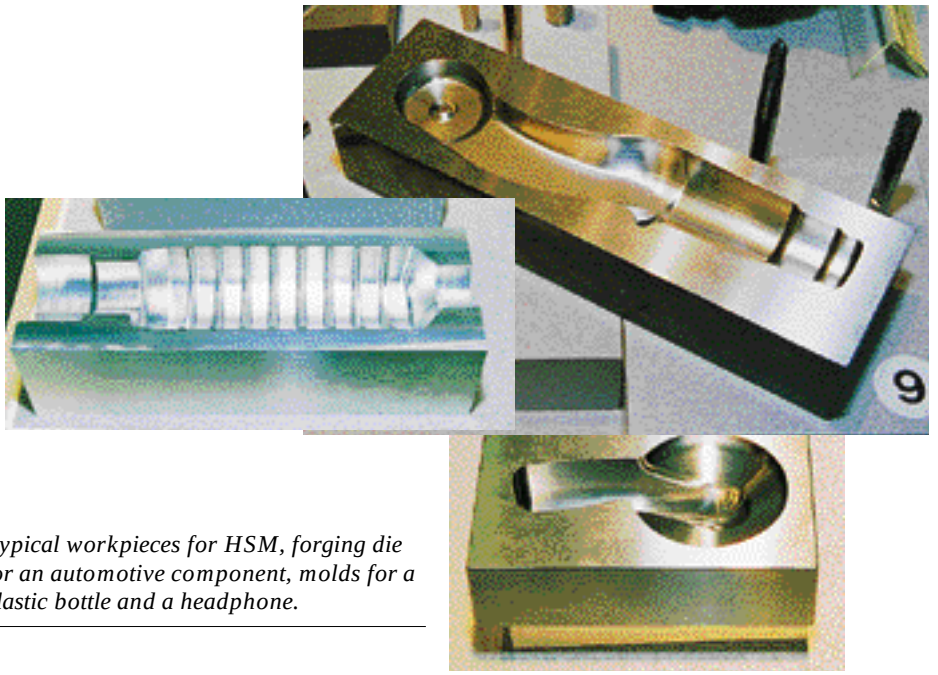
True v_c: 100 m/min, a_p: 6-8% of the cutter diameter, a_e: 35-40% of the cutter diameter, f_z: 0,05-0,1 mm/z

Semi-finishing

True v_c: 150-200 m/min, a_p: 3-4% of the cutter diameter, a_e: 20-40% of the cutter diameter, f_z: 0,05-0,15 mm/z

Finishing and super-finishing

True v_c: 200-250 m/min, a_p: 0,1-0,2 mm, a_e: 0,1-0,2 mm, f_z: 0,02-0,2 mm/z



Typical workpieces for HSM, forging die for an automotive component, molds for a plastic bottle and a headphone.

The values are of course dependent of out-stick, overhang, stability in the application, cutter diameters, material hardness etc. They should be looked upon only as typical and realistic values. In the discussion about HSM applications one can sometimes see that extremely high and unrealistic values for cutting speed is referred to. In these cases v_c has probably been calculated on the nominal diameter of the cutter. Not the effective diameter in cut.

One example:

- End mill with 90 degree corner, diameter 6 mm. Spindle speed at true cutting speed of 250 m/min = 13 262 rpm
- Ball nose end mill, nominal diameter 6 mm. a_p 0,2 mm gives effective diameter in cut of 2,15 mm. Spindle speed at true cutting speed of 250 m/min = 36 942 rpm

HSM Cutting Data by Experience

Material	Hardness	Conv. v_c	HSM v_e, R	HSM v_e, F
Steel 01.2	150 HB	<300	>400	<900
Steel 02.1/2	330 HB	<200	>250	<600
Steel 03.11	300 HB	<100	>200	<400
Steel 03.11	39 -48 HRc	<80	>150	<350
Steel 04	48-58 HRc	<40	>100	<250
GCI 08.1	180 HB	<300	>500	<3000
Al/Kirksite	60-75 HB	<1000	>2000	<5000
Non-ferr	100 HB	<300	>1000	<2000

Dry milling with compressed air or oil mist under high pressure is recommended.

Practical definition of HSM - conclusion

- HSM is not simply high cutting speed. It should be regarded as a process where the operations are performed with very specific methods and production equipment.
- HSM is not necessarily high spindle speed machining. Many HSM applications are performed with moderate spindle speeds and large sized cutters.
- HSM is performed in finishing in hardened steel with high speeds and feeds, often with 4-6 times conventional cutting data.
- HSM is High Productive Machining in small-sized components in roughing to finishing and in finishing and super-finishing in components of all sizes.
- HSM will grow in importance the more net shape the components get.
- HSM is today mainly performed in taper 40 machines.