Chapter 1

Machinability: Existing and Advanced Concepts

This chapter first analyzes the known concepts, definition and multiple methods, including the standard, of the assessment of machinability. It argues that having been developed a long time ago when cutting data for various tools were not widely and readily available, machinability, as a concept, became obsolete. As a result, the old notion of machinability means “all things to all men” and thus does not have any practical value nowadays, a fact admitted by leading tool suppliers, despite its colorful name which is still used in book, journal and paper titles.

This chapter presents an introduction to the basic ideas for the development of a new concept of machinability, arguing that the notion of machinability has a dual meaning: firstly, the *machinability of work material* which should be considered as an inherent property of the work material related to its physico-mechanical properties, and secondly, the *process machinability* which relates to a specific machining operation. The meaning, physical background and improvement of both machinabilities are discussed. It is revealed that the existing methods of enhancing the process machinability work well when their application reduces the specific energy of fracture of the layer being removed in machining. The role of tool geometry and the application of workpiece pre-heating (hot machining) and advanced plastic deformation (APD) of the work material are considered.

Chapter written by Viktor P. ASTAKHOV.

1.1. Introduction

In the literature on metal machining, machinability of the work material is defined as the ease with which it can be machined [SCH 02]. It is often pointed out that machinability depends on the properties of the work material, as well as on the cutting conditions. Therefore, it is not clear if machinability is an inherent property of a material or a property of the material in the particular machining system of components. This is the first and foremost issue that should be resolved for the proper definition of machinability and its assessment.

On the other hand, process developers, manufacturing engineers and practitioners in the machine shop may ask some logical questions: why do we need to know and understand the concept of machinability? What exactly can we gain using this knowledge? These are reasonable questions as no one has so far come up with a methodology that can calculate machinability yet also clearly show the gains one can obtain using the calculated result(s).

One problem is that machinability is a response variable that has not been clearly defined as it does not even have unit(s) with which to measure this qualitative notion. What exactly is it that one is trying to measure in any assessment of machinability? Traditionally, in the assessment of machinability, four "basic" factors are considered:

– Tool wear: tool life defined either by the number of machined parts, i.e. process economy, or by the cutting speed at which the criterion of tool life is achieved over the defined time, for example 20 minutes.

– Magnitude of the cutting force: tool and machine abilities to withstand this force, i.e. process feasibility.

– Chip shape: chip transportability from the machining zone, i.e. process feasibility.

– Roughness of the machined surface: quality of machining, i.e. process suitability.

Generally, the harder the work material or the higher its tensile strength, the more difficult it is to machine. However, copper is very soft, but difficult to machine because it is very ductile and chips do not break away, often leading to tool breakages. A higher carbon and alloy content usually makes steel more difficult to machine. Alloying elements in steels added for hardening characteristics (i.e. chromium, molybdenum, tungsten, etc.) increase the material strength and cause the material to work to harden, generally decreasing machinability. Nickel and aluminum tend to adhere to the cutting tool, causing a built-up edge which causes chipping and poor edge retention. The addition of some elements to alloys improves machinability. These include sulfur, phosphorous, lead, graphite, etc.

On the other hand, a harder work material may have greater machinability. For example, a material of hardness HRc 47 is the starting point of hard turning, while it is regularly performed on parts of hardness HRc 60 and even higher [AST 11A]. If the hardness of the work material is less than HRc 47 then hard tuning is not feasible. Another example is the machinability of a relatively hard, gray cast iron that is normally much greater than that of a soft austenitic stainless steel. Therefore, the hardness of the work material is not always a relevant parameter in comparisons of the machinability of various work materials.

The application of metal working fluid (hereafter called MWF), also known as coolant, aims to improve machinability, but sometimes actually inhibits it [AST 12]. The MWF type, brand, clearness, pH, flow rate and many other characteristics may affect machinability dramatically.

The cutting tool material is another factor that greatly affects machinability. For example, if a high-speed steel drill is used to machine a high-silicon aluminum alloy widely used in the automotive industry then machinability is low since the tool life and quality of drilled holes will be poor. On the other hand, if a PCD drill is used, then mirror-shining holes of close tolerance and a tool life measured in a hundred thousand holes are the direct results, so that the machinability in this case is excellent. Therefore, the tool material cannot be excluded from any machinability considerations.

Other factors that can affect machinability are the machine and its workholding fixture as they may define the ranges of available speeds and feeds as well as the range of vibration-free performance.

1.2. Traditional concepts of machinability and methods for its assessment

1.2.1. *Common perceptions*

The most common way to grade the machinability of various work materials is the so-called machinability comparison chart where the machinability of a given work material is measured as a percentage relative to the machinability of steel 1212 chosen to be 100% [TOO 83]. For example, the machinability of AISI steel 4140 is 55% according to this chart. A number of questions arise from this:

– What is the true meaning of this 55%? Is it related to the cutting speed, tool life, surface finish, chip control, etc.?

– Is this 55% valid for all machining operations from sawing to gear manufacturing?

– Is this 55% valid for any metallurgical state of steel 1040 in terms of hardness, grain size, etc.?

– Is this 55% still the same for any cutting tool, including the tool material and tool geometry, that can be used to machine this work material?

– How was this 55% obtained? What kind of tool (make, tool material, geometry), machining regime (cutting speed, feed, depth of cut), MWF (brand, chemical composition, concentration, flow rate, delivery system, etc.), machine (static and dynamic rigidity, alignment, accuracy of motions, etc.) was used in such a determination? What was actually measured and how?

Clearly, no answers to these practical questions can be found in the known machinability charts, which makes them worthless in the author's opinion.

More accurate data can be found in multiple machinability books developed by specialized manufacturing companies; for example, Metcut Co., which was founded in 1948, with the objective of developing and disseminating technical information in the science of machinability as claimed by its website[1]. The company has published a number of editions of *Machining Data Handbook* (e.g. [MAC 80]). This book contains machining recommendations including tool geometry, MWF, tool materials, surface finish and surface integrity. It provides guidelines for various machining processes. Using these data, the company developed an online data machinability database, CUTDATA, approximately 20 years ago. However, there are still some major concerns about the results obtained:

– Although it is called a machinability database, it has a little to do with this concept as it presents the recommended cutting data.

– It is not clear how this database was compiled. Obviously, the company developer did not conduct the cutting tests, results of which are included. Instead, these data were collected from various sources with no clear conditions of how they were obtained.

– The inputs are much too general. For example, the specification of the cutting tool material as HSS or carbide is not sufficient to determine the cutting data as there are great varieties in HSSs and carbides. For example, the operational cutting speed for two different grades of HSS (including proper coating) can differ by ten times for the same operation and work material. The tool life for the same operation and work material can differ by 5–10 times depending on the particular carbide grade and its coating.

1 http://www.metcut.com/metcut/metcutabout.html.

It is no wonder that this database did not have any further development and was thus gradually abolished.

Nowadays, manufacturing engineers and shop practitioners have different ways of selecting the proper tool (tool design, materials, coating geometry) and machining regime for any practical applications. One of the most common ways is through direct assistance from cutting tool manufacturers (catalogs and field application specialists), who recommend tools and machining regimes for particular jobs. Moreover, detailed and easy to use paper and online catalogs of major tool manufacturers and suppliers are available where known work materials are classified into machinability groups.

The leading cutting tool materials and cutting tool manufacturer Sandvik Coromant Co. finally admits in its latest catalog "Materials" that "*Machinability has no direct definition, like grades or numbers. In a broad sense it includes the ability of the workpiece material to be machined, the wear it creates on the cutting edge and the chip formation that can be obtained*." It is further explained that low alloy steel is considered to have a better machinability compared to stainless steel. The concept of "good machinability" usually means an undisturbed cutting action and a fair tool life. Most evaluations of the machinability for a certain material are made using practical tests, and the results are determined in relation to another test in another type of material under approximately the same conditions. In these tests, other factors, such as micro-structure, smearing tendency, machine tool, stability, noise, tool life, etc. will be taken into consideration. Other companies are still using the old-style table rating of machinability as shown in Figure 1.1. As such, no reference to 100%-machinability work material and no criteria for the listed percentages are given.

1.2.2. *Non-standardized tests for machinability assessment*

Mills and Redford published the only book on machinability of a wide variety of work materials [MIL 83]. In this book, machinability, considered as a property of the work material, has no generally accepted parameter for its measurement. As a result, machinability tends to remain a term which means "all things for all men". However, Mills and Redford suggested that consideration of the cutting energy should not figure in the definition of machinability and that this term should be understood to be some measure of the way in which a material wears away a cutting tool when it is being machined.

Workpiece materials – Machinability SECO

Nickel-base alloys	Machin-* ability (%)
Astroloy	14
Hastelloy B-2	20
Hastelloy C (plate)	25
Hastelloy C (cast)	20
Hastelloy C-22	20
Hastelloy C-276	18
Hastelloy C-4	18
Hastelloy G	18
Hastelloy G-3	18
Hastelloy N (bar, forge, ring)	20
Hastelloy N (cast)	18
Hastelloy S	25
Hastelloy W	18
Hastelloy X	18
IN 100	8

Titanium alloys	Machin-* ability (%)
Ti (pure) – (tube)	60
Ti (pure) – (plate, bar, forge, ring)	45
Ti 17	18
Ti 2Cu	30
Ti 3Al-2.5V (bar, forge)	25
Ti 3Al-2.5V (annealed tube)	60
Ti 4Al-4Mo-2Sn-Si	30
Ti 5Al-2.5 Sn (annealed)	35
Ti 5Al-2.5 Sn (ELI)	40
Ti 5Al-2.5 Sn	35
Ti 5Al-2.5 Fe	30
Ti 6-2-4-2 (precipitation hardened)	25
Ti 6-2-4-2 (annealed)	30
Ti 6-2-4-6 (precipitation hardened)	25
Ti 6-2-4-6 (annealed)	35

Cobalt alloys	Machin-* ability (%)
Air Resist 13	4
H531	6
Haynes 25	12
Haynes 188 (bar, forge, ring)	12
Haynes 188 (tube)	14
MP35N	16
MP 159	16
Stellite 21	16
Stellite 30	16
Stellite 31	16
W 152	16
WI 62	14
Mar-M-302	16
Mar-M-509	12

Figure 1.1. *Fragment of the Seco Co. machinability table*

In the author's opinion, Mills and Redford [MIL 83] built a logical trap for themselves because:

– Considering machinability as a property of the work material, Mills and Redford were forced to find a specific characteristic of the work material responsible for tool wear. Moreover, this characteristic should be measurable.

– Having selected a measure of the way in which the work materials wear away the cutting tool, Mills and Redford assumed that this measure is a property of the work material so all known tool materials ranging from high carbon tool steel to polycrystalline diamond (know as PCD) should be subjected to the same wear or wear type, not to mention a great range of cutting conditions resulting in a great variety of contact pressures and temperatures at the tool-chip and tool-workpiece interfaces.

– Mills and Redford shifted their attention to the place of wear (flank wear, crater wear, etc.) instead of the physics of wear. They admitted, however, that a fundamental understanding of the process of tool wear is lacking so it is not possible to combine basic properties of the work and tool materials as well as the cutting conditions to arrive at a measure of machinability.

– Having realized that the experimental determination of tool wear is highly uncertain, Mills and Redford concluded that the known tests and experimental data are valid only for the test conditions. As there a great variety of machining conditions in terms of tool materials and coatings, work materials and their metallurgical state, MWF parameters and grades, machining regimes, machine tool properties, part design etc., the machinability index becomes next to meaningless. Mills and Redford pointed out that even if the machinability test does attempt to compare the machinability of two different work materials for a given set of cutting conditions, there is no guarantee that when cutting conditions change the ranking will remain the same.

Mills and Redford [MIL 83] subdivided machinability tests into two basic categories: those which do not require one to carry out the actual machining and those which do. A parallel subdivision includes two more categories: those tests that merely indicate, for a given set of conditions, the relative machinability of two or more work-tool combinations (ranking tests) and those which indicate the relative merits of two or more work-tool combinations for a range of cutting conditions (absolute tests). A simple analysis, however, shows that for the results of the absolute test to be of any use, both the time spent and cost of the test tend to infinity.

Although Mills and Redford described the known non-machining tests to assess machinability [MIL 83], they did not present the critical analysis of these tests and their advantages and obvious drawbacks. Moreover, these tests are rather old and never considered as serious tests for standards or for any practical industrial applications. Nowadays, none of these tests have any practical use. Below are some obvious drawbacks to these tests:

– *Chemical composition test* is to correlate the chemical composition of the work materials with the 60-minute tool-life cutting speed. In the author's opinion, this test is meaningless as it is next to impossible to correlate the composition of the work material even with its mechanical properties. For example, the addition of a small percentage (or even a fraction of a percent) of manganese, as often used in the automotive industry, does not change the mechanical properties of the steel used for crankshafts, while machinability in terms of tool life and chip control varies to a wide extent.

– *Microstructural test*. The essence of this test is to reveal the correlation that allegedly exists between the metallurgical structure of low and medium carbon steels and their machinability. The problem is that much of the research involved in the development of this test did not note that the hardness and other essential mechanical and physical properties of the work material changed with its microstructure. For example, in the tests by Field and Zlatin [FIE 50], the hardness of the work material used changed from 100 HB to 420 HB, and, as well is known [ISA 00], the tensile as well as the yield strength changes in the same proportion. Therefore, this kind of test is meaningless unless one can change the microstructure keeping the hardness and other mechanical properties of the work material the same. As shown by Astakhov [AST 06], the only commercially available material that allows this is beryllium copper so the real influence of the microstructure of this material on the outcomes of the cutting process can be studied properly.

– *Physical properties tests*. The physical test described by Mills and Redford [MIL 83] attempted to correlate some mechanical and physical properties of the work material with the cutting speed v_{60} (that results in a 60-minute tool life). It is interesting to mention that two of the described tests involve the definition of the percentage reduction of area of the work material obtained from a conventional tensile test and its hardness. Although Mills and Redford pointed out that the main shortcoming of these tests is the lack of equipment necessary for obtaining these properties in the field, this is not so; these properties are well tabulated practically for all engineering materials. It is the author's opinion that although old and unused for a long time, these tests have more meaning in terms of physical insight into the definition of machinability as a property of the work material because they involve the strain characteristic (the elongation at fracture) and strength characteristic (hardness). Unfortunately, the further researchers and practitioners did not notice this advantage as they tried to use this test to determine machinability as the cutting process property which is incorrect as the basic equations for these tests do not include any parameters of the cutting process.

Discussing the machining test to assess machinability, Mills and Redford [MIL 83] pointed out nine tests of this type. As before, the advantages and drawbacks of these tests have not been analyzed; it was not pointed out that the process machinability rather than machinability of the work material is assessed in these tests.

According to the *constant pressure test*, the machinability is ranked by the feed rate achieved under constant feed force using the cutting tool of the predetermined geometry, tool material, etc. In the author's opinion, this test is in direct contradiction to the theory and practice of metal cutting as it utilizes the same tool geometry and material for various work materials. As is already known [AST 06], the selection of the cutting speed, tool material and multiple parameters of the tool geometry depend on the properties of the work material. In this test, however, these are kept invariable for various work materials to be compared, which is incorrect. *The rapid facing test* developed for high-speed steel tools features the same drawbacks as the constant pressure test, and it also involves the variable cutting speed, which adds even more uncertainty to the results.

The *tapping test* listed by Mills and Redford [MIL 83] as a machinability test actually has little to do with machinability although it is one of the most popular tests in recent years for MWF selection [AST 12, AST 06]. The test is carried out using the guidelines of the ASTM D 5619 standard. A high precision tap and a wide range of reproducible nut blanks are used. The results of this test can presumably be used for the evaluation of MWFs, tool life, tap design and the machinability of metals. The determination of cutting efficiency is based on an accurate and fast measurement of the cutting torque, exerted on nut blanks. The ASTM D 5619 standard considers this method to be the only acceptable method of data evaluation, while methods based on power consumption by the driving motor are not considered to be accurate enough. The average of any segment of a torque curve can be studied using a computer data acquisition system. The obtained cutting torque is considered to be the measure of machinability. The major drawbacks of this test are obvious:

– because high-speed steels threading taps are used as the cutting tool, the cutting speed is low, i.e. it is at least ten times lower than that used even for high-speed steel tools used in other machining operations, not to mention carbide, CBN, PCD, ceramic and other cutting tool materials;

– the tool geometry of threading taps is unique in terms of the flank and rake angles and does not resemble even remotely that of the various cutting tools used for other machining operations such as turning, milling, drilling, etc. For example, the clearance angle on the tap cutting teeth is twenty times smaller than that used for single-point cutters and drills. As a result, the contact conditions at the tool–workpiece interface that define flank wear are considerably different.

The essence of the *degraded tool test* is to assess the machinability of the work materials by cutting them with softened cutting tools. As the properties of the tool material, cutting regime (thus the forces, temperatures, etc.), tool geometry and other essential parameters of the cutting process are not considered to be the essential factors affecting machinability of the work material, this test attempts to assess machinability as a property of the work material. Unfortunately, the test results are not treated as such, and so the technical merit of this test is questionable.

The *accelerated wear test* is a kind of mirror image of the degraded tool test with the same significance of the end result. The test is conducted at high cutting speed to accelerate tool wear. The amount of this wear is then used to assess machinability of the work material. As with the degraded tool test, this test attempts to assess machinability as a property of the work material as the cutting conditions do not resemble those used in practice.

1.2.3. *Standard tests*

1.2.3.1. *ISO (ASME) test*

Although often referred to as machinability standards, the international standard ISO 3685 "Tool-Life Testing with Single-Point Turning Tools" and its analog ANSI/ASME "Tool-life Testing With Single-Point Turning Tools" (B94.55M-1985) can hardly be considered as directly related to machinability because these standards present the rather obsolete methodology for tool-life testing where one parameter is changed at a time [AST 04]. Both standards consider the rake and flank tool wear types and patterns as they are well described in the literature on metal cutting [AST 06, AST 04, AST 08a, SHA 84].

Standard tool life testing and representation includes Taylor's tool-life formula [TAY 07]

$$vT^n = C_T \qquad [1.1]$$

where v is the cutting speed in meters per minute, T is the tool life in minutes, C_T is a constant into which all cutting conditions affecting tool life must be absorbed.

Although Taylor's tool-life formula is still in wide use today and is at the very core of many studies on metal cutting including at the level of national and international standards, one should remember that it was introduced in 1907 as a generalization of 26 years of experimental studies conducted in the 19th Century using the work and tool materials and experimental techniques available at that time. Since then, each of these three components has undergone dramatic changes. Unfortunately, the validity of the formula has never been verified for these new conditions. So far, nobody has proven that it is still valid for any cutting tool materials other than carbon steels and high-speed steels, for cutting speeds higher than 25 m/min.

Figure 1.2 shows the experimental procedure of determining Taylor's formula coefficients according to standard ANSI/*ASME* B94.55M-1985 for three cutting speeds $v_1 > v_2 > v_3$ [AST 08a]. A simple analysis of Taylor's tool-life formula shows that it actually correlates cutting temperature with tool life as the cutting speed solely determines the cutting temperature. As can be seen, this formula states that the higher the cutting speed (temperature), the lower the tool life, which is in direct contradiction with well-known experimental studies and the practice of metal cutting [AST 08a]. Leading tool manufacturers clearly indicate the favorable range of cutting speeds (temperatures) for their tool materials. Deviation from the recommended speed (temperature) for a given tool material on either side lowers tool life. This, however, does not follow from Taylor's tool-life formula.

Tool life, considered according to the standards as the operating time until the selected tool failure criterion is reached, does not reflect the cutting regime and thus does not reflect the real amount of work material removed by the tool during the time over which the measured flank wear is achieved. In this sense, this tool life does not have much meaning. Moreover, this tool life is particular and thus, in general, is not suitable for the optimization of machining operations, the comparison of various cutting regimes, the assessment of various tool materials and so on. For example, it is not possible to compare two different tool materials if two different cutting speeds (suitable respectively for each one in particular) were used in the tests.

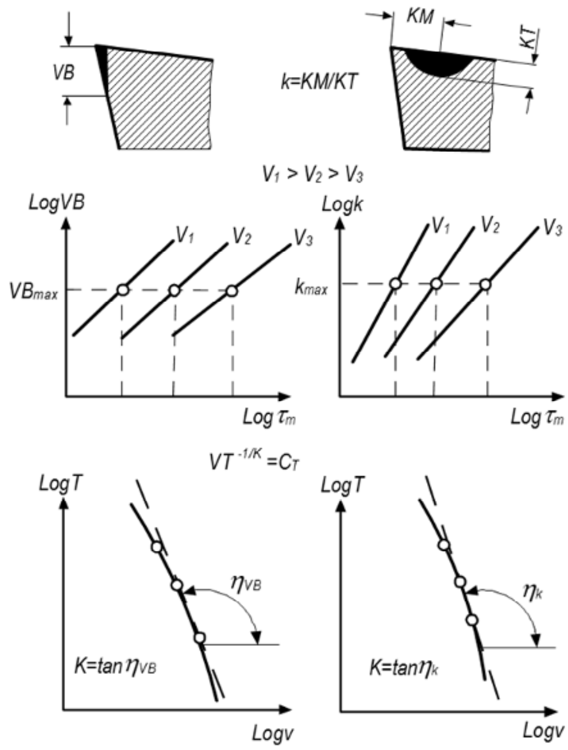

Figure 1.2. *Experimental procedure of determining of Taylor's formula coefficients according to standard ANSI/ASME B94.55M-1985*

Another significant drawback of this methodology for machinability assessment is that tool life is considered as the only parameter of machinability leaving other essential parameters, for example surface integrity, accuracy of machined parts, chip control, etc., out of consideration. In modern manufacturing where the machining quality and process efficiency are of prime concern and where advanced machines with spindles and controllers are capable of measuring force factors and in-process machining quality, tool wear is no longer considered to be the prime criterion of machinability. Instead, a certain combination of quality parameters such as, for example, diametric accuracy and surface roughness, are of prime concern. So machinability is "silently" considered to be the ability of a given machining operation to achieve the pre-set quality requirements for a given work material while keeping a pre-defined level of process efficiency.

1.2.3.2. *ASTM test*

Standard ASTM E618-07 “Standard Test Method for Evaluating Machining Performance of Ferrous Metals Using an Automatic Screw/Bar Machine” was written to fill a requirement for a standard test for determining the machinability of ferrous metals using automatic screw/bar machines. Machinability is considered to be a suitability of a particular work material for producing parts of the standard design in such machines to a uniform level of quality with respect to surface roughness and size variation. The standard intends to simulate mass production conditions in a controlled environment using a single- or multi-spindle automatic screw machine. The essence of the standard is to compare production rate in manufacturing the standard part shown in Figure 1.3. The part is designed to make use of the three most common screw machining operations: rough turning, finish turning and twist drilling. The part is machined from bar stock of 1” (25.4 mm) dia. The diametric tolerances and surface roughness are the control parameters.

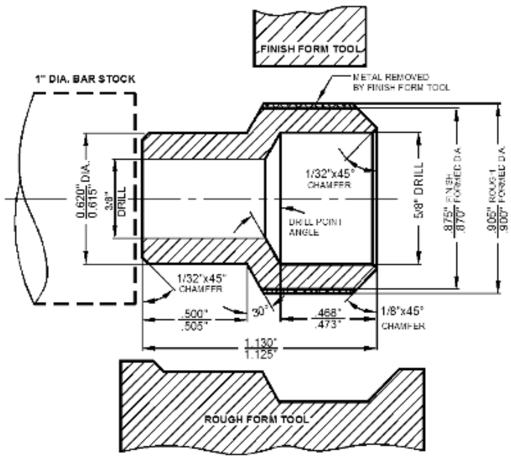

Figure 1.3. *Automatic screw machine part required for ASTM E618*

The machinability of a material is measured by the maximum production rate at which test pieces can be produced to specified surface roughness and size limits for specific periods of time and by the cutting speed and tool-feed rate to attain this production rate. The tool geometry and the tool materials (HSS M2 for the form tools and M7 for the drills) are fixed by the standard. The machining sequence is specified by the standard and is based on normal industrial practice. Some recommendations for the calibration of a screw machine to be used for testing are also given.

The standard points out that “the machining performance (or, as it sometimes called, the “machinability”) of material cannot be regarded solely as a property characteristic of that material. The principal indexes of machining performance, namely, production rates, cutting speeds, and tool-feed rates, are generally affected by many other factors, such as the tool material, the surface roughness, and dimensional limits demanded of the product, the coolant and its properties, and the configuration of the part. These latter factors are quite independent of the work material and yet all affect its machining performance criteria.”

The standard admits that testing according to this standard is neither simple nor inexpensive. Substantial quantities of the test material are required, varying from a few hundred kilograms to a few thousand. A significant amount of time is required to compare different work materials including finding the proper regimes, the machining itself, and part quality evaluation.

The standard is the first, and so far the only, attempt to evaluate machinability instead of other output characteristics of the metal cutting process. It provides a detailed testing methodology that concerns various aspects of the metal cutting system including the determination of machine capability, test piece design, cutting tool design and geometry, etc. The standard has a number of obvious shortcomings:

– It uses obsolete tool designs and tool material that are hardly used in today’s manufacturing practice. The eight-hour tool life required by the standard is not efficient for modern machine tools.

– The most uncertain place in the test methodology suggested by the standard is the selection of the cutting speed and cutting feed (tool-feed rate) to assure an eight-hour tool life for all three tools (the rough and finish form tools and twist drill). The standard recommends such a selection on the basis of experience or general guidelines for a ferrous metal of similar composition and conditions. However, if one knows the cutting speed and cutting feed to assure an eight-hour tool life, the reason for conducting the test at the production rate required by the standard at the tests’ outcome can simply be calculated. On the other hand, if these parameters are unknown, their determination by the trial-and-error methods may take virtually forever, including tons of wasted work material and many machine and man hours.

1.2.3.3. *American Iron and Steel Institute (AISI) test*

The AISI Bar Machinability Subcommittee was formed in 1991 and was composed of representatives from automotive OEMs, academia and the steel industry. It aimed to develop information needed by the machining industry for material selection, process development and for improving the understanding of the factors that influence the machinability of steel. To accomplish this task, more than

30 industrially significant steel grades and their variants were evaluated in the ensuing years.

The test materials were produced by eight different steel companies using various melting and casting practices. Material properties and microstructures were characterized and the machinability of each steel variant was evaluated by at least two different machinability testing laboratories. A study of the machinability of more than 30 industrially significant carbon, alloy, resulfurized and microalloyed steel grades using carbide tools in a standardized single point turning test was conducted. It was found that machining data generated with high-speed steel tooling could not be directly extrapolated to applications involving carbide tooling. The plain carbon and alloy steels were found to have a v_{30}-tool life that correlated well with their Ito-Bessyo Carbon Equivalent when fitted to a 3rd order polynomial. It was also found that the machinability of 1200 series, 1100 series, microalloyed and leaded steels followed the same relationship. The values of the cutting speed corresponding to a 30-min tool life, v_{30}, were generated in this study and suggested to be used for guidance in selecting machining parameters for the steel grades tested. The v_{30} tool life of other steel grades can be approximated by calculating their Ito-Bessyo Carbon Equivalent. It is suggested that the database thus generated can be used by the machining industry to compare the relative machinability of various steel grades and their properties to make more informed decisions about the application of materials.

In establishing a machinability test standard, a number of factors were considered based on the discussions of the AISI Machinability Roundtable participants. First, the test procedure must not be so complex that it discourages its use. The ISO 3685 standard is quite complete, essentially covering all aspects of single point turning. However, it was the general consensus of the committee that only those features of the ISO 3685 relating to turning tests conducted with carbide tooling be addressed in the current standard. The standard test must be easy to conduct, and the cutting conditions well defined and clearly specified. A second concern was one of the reliability and transportability of standard test data. This was addressed in a round-robin series of turning tests conducted with SAE1141, SAE1541 and SAE4140 steels. The preliminary tests established the reproducibility of the testing based on the proposed standard. To ensure this level of reproducibility continued between the different testing laboratories, a standard baseline material (SAE1045) was selected as a reference. All participating laboratories conducted the standard turning test on this material.

In the author's opinion, the result of this enormous effort is rather humble. The Machinability Estimator was developed for carbon and alloy steels using uncoated carbide tools and is available online in the form of an Excel table[2]. One simply needs to input the chemical composition of a steel, i.e. the content of carbon, silicon, manganese, sulfur, nickel, chromium, molybdenum, copper and vanadium. The estimator will return a value of the Ito-Bessyo carbon equivalent and the estimated cutting speed v_{30}. No other essentials for machinability mechanical properties, such as hardness, strength, grain size, etc. (which vary significantly with heat treatment of a steel), no tool material nor its geometry, no MWF parameters nor other essentials of a particular machining operation are accounted for.

1.2.4. *Assessments used in machining practice*

Some "down-to-earth" estimates of machinability of a particular work material are used in practices of process design and assessment of its efficiency. As the prime criterion of machinability, the cutting speed v_T corresponds to a certain pre-defined tool life T = 15, 20 or 30 min. As such, v_T is correlated with work material hardness (HB, HRC), tensile strength, ultimate (σ_{UTS}), tensile strength, yield (σ_Y), true ultimate tensile strength (*Su*), chemical composition or even with some combination of strength and physical characteristics as the true ultimate tensile strength and thermal conductivity, k_w. Some of such empirical relationships are as follows:

$$
\begin{aligned}
v_T &= C_1/(HB)^{n_1} \\
v_T &= C_2/(HRC)^{n_2} \\
v_T &= C_3/(\sigma_{UTS})^{n_3} \\
v_T &= C_4/(S_u)^{n_4} \\
v_T &= \frac{C_5 (k_w)^{n_5}}{(S_u)^{n_6}} \\
v_T &= \frac{C_6}{\prod_{i=1}^{m} (1 + j_i E_i)}
\end{aligned}
\qquad [1.2]
$$

where $C_1 \ldots . C_6$, $n_1 \ldots n_6$ are empirically determined constants, $E_1 \ldots E_m$ are a percentage of the considered m alloying elements, $j_1 \ldots j_m$ are the relative impact of the considered alloying element on v_T.

2 https://steel.org/en/sitecore/content/Autosteel_org/Web%20Root/Programs/Bar%20 Machinability.aspx.

Having had practical purposes for many years of metal cutting history, the discussed estimates can be considered as another proof of the inability of the prevailing metal cutting theory to offer any help to practical manufacturing.

1.2.5. *The merit of the known concepts of machinability*

The ongoing analysis leads to discouraging conclusions. Having been developed a long time ago when cutting data for various tools were not widely and readily available, machinability, as a concept, became obsolete. Machinability means "all things to all men" and thus does not have any practical value nowadays as admitted by leading tool suppliers, despite its colorful name which is still used in book, journal and paper titles. In the author's opinion, however, these seemingly obvious conclusions, logically derived from the ongoing analysis, are not entirely incorrect.

When physics-based and real-world fact supported theory of metal cutting is used, the concept of machinability is very useful and productive in the optimization of the metal cutting process. The sections to follow present an introduction to the basic ideas of the development of a new concept of machinability.

1.3. Knowledge-based foundations of machinability

1.3.1. *Practical need*

Although machinability has been of interest since the era of the Egyptian pyramids, the known advancements into studies of its characterization have been rather modest. The most apparent cause for this is that studies on machinability lacked a systemic approach, i.e. one component, for example tool life, was studied while other important parameters, e.g. process efficiency, were not considered. Although this is true, this is not the real cause in the author's opinion. The real cause is that neither the machining system as a whole nor its components were ready for the implementation of possible findings.

In the not-too-distant past, the components of the machining system were far from perfect in terms of assuring normal tool performance, and thus gaining any application advantage of advanced machinability concepts was not possible. Tool specialists (design, manufacturing and application) were frustrated by old machine tools with spindles that could be shaken by hand, part fixtures that clamped parts differently every time, part materials with inclusions and a large scatter in the essential properties, tool holders that could not hold tools without excessive runouts assuring their proper position, starting bushing and bushing plates that had been used for years without replacement, low-concentration, often contaminated MWFs which brought more damage than benefit to cutting tools, manual sharpening and pre-setting of cutting tools, limited ranges of cutting speeds and feeds as well as insufficient power available on machines, low dynamic rigidity of machines, etc. As a result, any further development to improve machining performance was discouraged as manufacturers did not see any return on the investments in such developments.

This has been rapidly changing since the beginning of the 21st Century as global competition has forced many manufacturing companies, first of all automotive manufacturers, to increase the efficiency and quality of machining operations. To address these issues, leading tool and machine manufacturers have developed a number of new products – new powerful precision machines having a wide range of speeds and feeds, tool materials and coatings, new tool holders, automated part fixtures, advanced machine controllers, etc. These changes can be called the "silent" machining revolution as they are rather dramatic and occur in quite a short period of time (referred to in recent manufacturing publications as the 4^{th} Industrial Revolution). As the cost of machining time and labor increased significantly, machining efficiency became of prime concern. As a result, a fresh look at the machinability of various materials from the point of view of their efficient machining has become common, so that the need for the proper determination of machinability has made machining studies become imminent. The response of the scientific community to this challenge has been rather modest so far.

1.3.2. *Ability of the prevailing metal cutting theory*

Although metal cutting, or simply machining, is one of the oldest processes for shaping components in the manufacturing industry and it is widely quoted that 15% of the value of all mechanical components manufactured worldwide is derived from machining operations, machining remains one of the least understood manufacturing operations due to the low predictive ability of machining models [USU 82, USU 88] despite its obvious economic and technical importance. In the author's opinion, this is due to the commonly held notion that new surfaces in metal cutting are formed simply by "plastic flow around the tool tip" [SHA 84]. It other words, the metal cutting process is one of the deforming processes where a single-shear plane model of chip formation constitutes the very core of metal cutting theory, and thus this process is thought of primarily as a cutting tool deforming a particular part of the workpiece by means of shearing. Although a number of cutting theories and the FEM models/commercial packages have been developed based on this concept, their prediction ability is low so that they are not used in any practical process design and optimization of cutting parameters [AST 11B].

The major problem is that metal cutting is not a deforming process in the sense used today [AST 10]. To show this, one can consider the state of the art in the closely-related deforming process used in industry. Until 10 years ago, the design of metal forming tools was mostly based on knowledge gained through experience, and the design of optimal tools often required protracted and expensive trial-and-error testing. Today, even in the earlier phases, simulations of the forming process are carried out using FEMs. The most important goals of such simulations are the verification of manufacturability of the sheet-metal parts and obtaining vital information on the optimal tool design. As a result, great savings have been achieved due to the introduction of process simulation in metal forming. These savings originate from the faster development of tools and from the dramatic shortening of trial-and-error testing. In recent years, tool development and production time has been reduced by about 50% due to the used of simulations and a further 30% reduction over the next few years appears realistic. The simulation of forming tools has already reached the stage where its results can be fed directly into the press tool digital planning and validation process. Thus, today, starting from the design model and throughout practically all process steps as far as the actual design of the press tool, the production of a component can be fully simulated before a first prototype is built [ROL 08].

Obviously, this is not nearly the case in metal cutting where the development of sound criteria of machinability is crippled by inadequate theory. The problem is that the single-shear plane model used as the foundation of this theory does not resemble the reality, even to a first approximation [AST 05].

In a deforming process, ductility is the most desired property of the work material, while in metal cutting, ductility causes totally useless plastic deformation of the work material in its transformation into the chip. As discussed by the author previously in the analyses of the energy partition in the cutting system [AST 06, AST 05, AST 08B] more than 70% of the energy required by the cutting system for its existence is spent on plastic deformation of the layer being removed, i.e. actually wasted as the deformed chip does not serve any useful purpose. This is the major difference between metal cutting and deforming operations used in industry. Unless this is clearly realized by the researchers and practitioners in the field, no progress in metal cutting modeling can be achieved.

1.3.3. *Notion of two kinds of machinability*

In the author’s opinion, the notion of machinability has a dual meaning. First, the *machinability of work material* which should be considered as an inherent property of the work material related to its physico-mechanical properties. Second, the *process machinability* of material that relates to the machinability of the material in a specific machining operation. Although these two notions are closely related, they are not nearly the same. The first should be considered as the ultimate goal in the optimization of the metal cutting process, while the second relates to the reduction of the first machinability due to the real-world process efficiency.

The two notions of machinability introduced can be used for:

– the development of new materials with enhanced machinability without compromising their service properties;

– assessments of the machinability of existing materials and to point out possible the direction of machinability improvements;

– assessments and optimization of the metal cutting process and operation efficiency through the concept of process machinability and physical efficiency of the cutting system previously introduced by the author [AST 06].

The following sections aim to explain the concepts introduced, presenting practical ways for the determination of machinabilities according to these concepts and their use in the metal cutting process optimization.

1.3.4. *Machinability of the work material*

1.3.4.1. *Proposed concept*

Among the many possible criteria of machinability of a given work material, the most relevant should be chosen according to the following requirements:

– it should have direct correlation with the ease with which it can be machined, i.e. with the initial definition of machinability;

– it should be a sole property (mechanical, physical, chemical, etc.) or a combination of the properties of the work material;

– it should be able to be determined relatively simple with the necessary accuracy.

According to the definition previously presented by the author [AST 98], the process of metal cutting is like a deforming process, which takes place in the components of the cutting system that are so arranged that the external energy applied to the cutting system causes the purposeful fracture of the layer being removed. As a result, the energy (mechanical work) needed for fracture of a unit volume of the work material was suggested as its machinability criterion. As such, as the machinability of a work material is defined as energy, it has units of energy (J) and becomes the objective property of the work material, which can be measured using mechanical testing of this material.

The energy needed for fracture of the unit volume of the work material is the area under the true stress-strain curve considered up to fracture, known as the damage curve [ABU 11]. Figure 1.4 shows the comparison of the real damage curve with that used in the modeling of metal cutting. As can be seen, the curve used in modeling (the hypothetic undamaged stress-strain curve) does not have the right-side limit, i.e. the work material is assumed to deform to infinity so that there is no well-defined area under this curve. On the contrary, the real damage curve which describes behavior of the work material in fracture has a well-defined, and thus measurable, area.

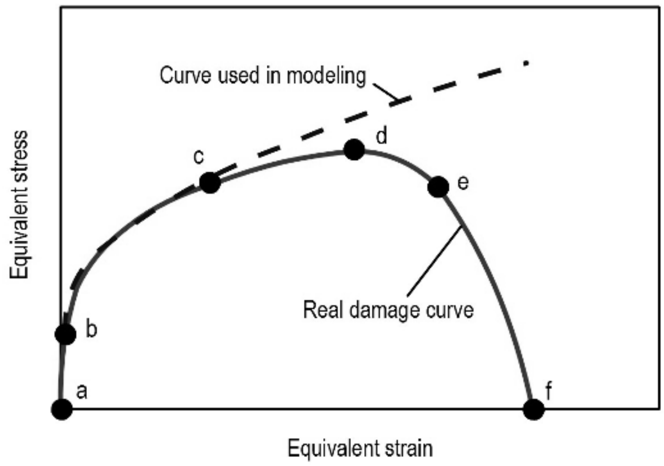

Figure 1.4. *Comparison of the real damage curve with that used in modeling of metal cutting*

The elastic-plastic undamaged path *abc* is followed by the departure of the experimental yield surface from the undamaged yield surface at point *c*. Point *c* can be considered as the damage initiation site where the material hardening modulus becomes progressively sensitive to the amount of damage leading to the declination of the material loading capacity. The hypothetic damage initiation site *c* also marks the start of elasticity modulus degradation. Due to increased damage, the material reaches its ultimate stress capacity at *d* where the hardening modulus becomes zero. This usually occurs in ductile metals when the material loading capacity decreases by 30% to 70% of its full capacity due to the accumulated damage [ZHA 11]. The observed fracture initiation site is denoted by point *e* and finally the failure is indicated by point *f*. When the strain at fracture $\overline{\varepsilon}_{p-f}$ (strain at point *f*) is known, then the area under the strain-stress curve is calculated as [AST 98]

$$E_f = \int_0^{\bar{\varepsilon}_{p-f}} \bar{\sigma} d\bar{\varepsilon}_p \qquad [1.3]$$

1.3.4.2. *Comparison with the known experimental assessment of machinability of difficult-to-machine materials*

To verify the validity of the introduced machinability criterion, Yaroslavtsev [YAR 12] compared the specific fracture energy (E_f (GJ/m^3)) of five groups of advanced work materials with the experimental data presented as machinability coefficients of these materials with respect to AISI 321 work material. Such coefficients were obtained as ratios of the limiting cutting speed for a given work material to the limiting speed for AISI 321. Groups II–VI, as classified by Gurevich *et al.* [GUR 86], of difficult-to-machine materials including titanium alloys were included in the study. Tables 1.1 through 1.5 present the chemical composition of these materials.

Components	Alloy II-1	Alloy II-2	Alloy II-3	Alloy II-4	Alloy II-5
C	0.10–0.16	0.16–0.24	0.11–0.17	0.09–0.13	0.2–0.3
Si	≤ 0.6	≤ 0.6	≤ 0.6	≤ 0.6	≤ 0.6
Mn	≤ 0.6	≤ 0.6	≤ 0.6	≤ 0.6	≤ 0.6
Cr	10.5–12.0	12.0–14.0	16.0–18.0	10.5–12.5	11.0–13.0
Ni	1.5–1.8	-	1.5–2.5	1.5–1.8	1.5–1.8
Mo	0.35–0.50	-	-	0.35–0.50	1.2–1.9
W	1.6–2.0	-	-	1.6–2.0	1.6–2.0
V	0.18–0.30	-	-	0.18–0.30	0.18–0.30
Fe	Bal.	Bal.	Bal.	Bal.	Bal.
S	≤ 0.025	≤ 0.025	≤ 0.025	≤ 0.025	≤ 0.030
P	≤ 0.030	≤ 0.030	≤ 0.030	≤ 0.030	≤ 0.030

Table 1.1. *Chemical compositions of alloys of Group II*

Components	Alloy III-1	Alloy III-2	Alloy III-3
C	≤ 0.12	≤ 0.08	0.09–0.14
Si	≤ 2.0	≤ 0.8	≤ 0.8
Mn	≤ 0.6	≤ 0.8	≤ 0.8
Cr	17.0–19.0	14.0–16.0	20.0–22.0
Ni	9.0–11.0	7.0–9.4	4.8–5.8
Ti	0.8	–	0.25–0.50
Al	–	0.70-1.3	≤ 0.08
Fe	Bal.	Bal.	Bal.
S	≤ 0.02	≤ 0.025	≤ 0.025
P	≤ 0.035	≤ 0.035	≤ 0.035

Table 1.2. *Chemical compositions of alloys of Group III*

The listed alloys were subjected to mechanical testing to determine their mechanical properties and specific fracture energy as the area under the real damage curves. Table 1.6 lists K_vs obtained through an extensive experimental program, the experimentally obtained mechanical properties of the listed work materials for all tested materials, and specific fracture energies for these materials obtained as the areas under the corresponding damage curves (E_f (GJ/m^3)).The verification of the proposed criterion of machinability of the work material was carried out by comparison of K_vs and corresponding E_fs. To avoid the influence of any possible difference in the contact conditions at the tool-chip and tool-workpiece interfaces and other particularities of the cutting process, work materials from the same groups were compared. This is because the discussed groups were selected accounting for the composition and properties of the discussed materials, i.e. the contact conditions for the work materials from the same group were almost the same.

Figure 1.5 shows the verification chart. In this chart, the solid lines correspond to the test temperature 273 K. As can be seen, a good correlation of the proposed criterion of machinability and test results is the case. This correlation is still great for a test temperature of 673 K (the dashed lines in Figure 1.5) that corresponds to the maximum temperature in the deformation zone in cutting. Therefore, the proposed criterion of the work material machinability can be used for machinability assessments with no cutting tests. Using the proposed criterion, the effectiveness of any change in the material composition, mechanical properties, and the metallurgical structure in terms of improving machinability of a given work material can easily be evaluated using standard material testing equipment.

Components	Alloy IV-1	Alloy VI-2	Alloy VI-3	Alloy VI-5
C	0.4–0.5	0.08–0.12	0.38–0.43	≤ 0.10
Si	≤ 0.8	≤ 0.6	0.3-0.8	≤ 1.0
Mn	≤ 0.7	1.00–2.00	7.5–9.5	≤ 1.0
Ni	13.0–15.0	24.0–27.0	7.0–9.0	18.0–21.0
S	≤ 0.02	≤ 0.018	≤ 0.03	
P	≤ 0.035	≤ 0.025	≤ 0.035	
Ti	–	–	–	2.6–3.2
Cr	13.0–15.0	15.0–17.0	11.5–13.5	10.0–12.5
Mo	0.25–0.40	0.25–0.40	1.1–1.4	–
W	2.00–2.75	2.00–2.75	–	–
Cu	≤ 0.3	–	≤ 0.3	–
N	–	0.10–0.20	–	–
Fe	Bal.	Bal.	Bal.	Bal.
V	–	–	1.25–1.55	–
Al	–	–	–	≤ 0.80

Table 1.3. *Chemical compositions of alloys of Group IV*

1.3.4.3. *Basic methods of improvement of machinability of work materials*

Measures to improve the machinability of materials primary include: (a) free-machining additives (machining aids), and (b) microstructure modification through heat treatments (e.g. annealing and normalizing).

Components	Alloy V-1	Alloy V-2	Alloy V-3	Alloy V-4
Fe	–	–	37.5–47.4	–
C	≤ 0.07	≤ 0.07	≤ 0.08	≤ 0.10
Si	≤ 0.60	≤ 0.60	≤ 0.60	≤ 0.60
Mn	≤ 0.40	≤ 0.40	≤ 0.60	≤ 0.30
Ni	70.1–77.4	70.1–77.4	33.0–37.0	Bal.
S	≤ 0.007	≤ 0.007	≤ 0.02	≤ 0.011
P	≤ 0.015	≤ 0.015	≤ 0.035	≤ 0.015
Cr	19.0–22.0	19.0–22.0	14.0–16.0	8.5–10.5
W	–	–	2.5–3.5	4.3–6.0
Ce	≤ 0.02	≤ 0.02	–	≤ 0.02
Ti	2.4–2.8	2.4–2.8	2.4–3.2	-
Al	0.6–1.0	0.6–1.0	0.7–1.4	4.2–4.9
B	≤ 0.003	≤ 0.003	≤ 0.02	≤ 0.02
Pb	≤ 0.001	≤ 0.001	–	–
Co	–	–	–	4.0–6.0

Table 1.4. *Chemical compositions of alloys of Group V*

1.3.4.3.1. Free machining additives

Free-machining additives enhance the machinability of the work material because they promote microcracking and thus reduce the energy needed for fracture of the layer being removed from the rest of the workpiece when machinability as a property of the work material is considered. In the consideration of the process machinability, such additives:

– promote chip breakage, which results in much shorter chips that may significantly improve swarf removal from the machining zone (to prevent re-cutting) and the machine through chip conveyers (to prevent machine downtime for chip cleaning);

– improve the machining process as a whole. This general statement should be considered on a case-by-case basis. For example, in high-speed machining, they create better conditions (frictional and adhesion-preventive) at the tool–chip and tool–workpiece interfaces and thus increase tool life. They also lower cutting temperature, which reduces the machining residual stress in the machined parts (both superficial and in-depth). In the machining of difficult-to-machine materials (normally machined in low cutting speeds), additives to the work material reduce the built-up edge formed on the rake face of the tool at low speeds, which decreases both surface roughness of the machined surface and adhesion tool wear.

Components	Alloy VI-1	Alloy VI-2	Alloy VI-3	Alloy VI-4
Al	–	4.0–5.5	4.5–6.5	4.5–6.2
Cr	–	–	–	1.0–2.5
Mo	–	–	–	1.0–2.8
V	–	–	3.5–4.5	–
Fe	≤ 0.25	0.30	0.3	1.5
Si	0.15	0.15	0.15	0.40
C	≤ 0.08	0.10	0.10	0.10
N	≤ 0.05	0.05	0.05	0.05
O	≤ 0.15	0.15	0.15	0.15
H	≤ 0.012	0.015	0.015	0.015
Zr	–	–	–	0.30

Table 1.5. *Chemical compositions of alloys of Group VI*

It is obvious that the composition and amount of free-machining additives depend on the type of work material, and thus vary to a wide extent. The composition and amount of free-machining additives to titanium and its alloys are considered in this section as an example.

Pure titanium and titanium alloys find applications in the parts of high-speed vehicles such as aircraft and automobiles due to their light weight and high strength. However, in the manufacture of parts from titanium or a titanium alloy by machining, the poor machinability of the material limits the tool life and the machining speed. Therefore, the machining process is costly and time consuming and the mass production of titanium or titanium alloy parts has been difficult. This is one of the reasons for the high costs of titanium or titanium alloy products. It has been known that the machinability of titanium and titanium alloys is inferior to that of steels. The poor machinability of titanium and titanium alloys is thought to result from (a) an increased force imposed on the rake face of a cutting tool due small tool-chip contact length, which causes the cutting wedge to be readily damaged; (b) an increased cutting temperature, i.e. the temperature in the cut area due to the lower thermal conductivity of titanium and its alloys compared to steel; and (c) a higher susceptibility of titanium to react with the cutting tool than with steels as evidenced by the fact that titanium is more reactive to other elements than steel.

No	Alloy	K_v	Standard mechanical properties				Properties of the real damage curve	
			σ_{UTS} (MPa)	σ_Y (MPa)	δ (%)	ψ (%)	S_u (MPa)	E_f (GJ/m^3)
1	Alloy II-1	1.3	1000	790	11	55	1640	1.054
	Alloy II-1*	–	820	660	8.5	52	1320	0.784
2	Alloy II-2	1.3	710	450	21	63	1230	0.963
	Alloy II-2*	–	530	370	17	61	910	0.676
3	Alloy II-3	1.0	1080	820	17	58	1810	1.252
	Alloy II-3*	–	940	730	13	54	1530	0.960
4	Alloy II-4	0.5	1670	1160	7	50	2650	1.488
	Alloy II-4*	–	1420	1080	5	47	2200	1.145
5	Alloy II-5	0.3	1770	1470	14	51	2830	1.640
	Alloy II-5*	–	1570	1290	12	48	2450	1.312
6	Alloy III-1	1.0	610	240	41	63	1280	0.875
	Alloy III-1*	–	440	200	31	65	920	0.683
7	Alloy III-2	0.9	1040	610	24	55	1530	1.023
	Alloy III-2*	–	820	520	6	56	1270	0.855
8	Alloy III-3	0.85	720	420	19	63	1510	1.087
	Alloy III-3*	–	540	370	32	68	970	0.867
9	Alloy IV-1	0.8	780	400	10	37	1120	0.418
10	Alloy IV-2	0.6	860	490	20	36	1220	0.443
11	Alloy IV-3	0.45	940	600	17	36	1460	0.511
12	Alloy IV-4	0.45	1020	580	24	34	1520	0.481

Table 1.6. *Machinability coefficients and actual test data for the work materials*

13	Alloy V-1	0.32	1040	610	29	24	1370	0.279
14	Alloy V-2	0.32	1010	660	21	19	1260	0.220
15	Alloy V-3	0.24	1160	690	19	23	1500	0.302
16	Alloy V-4	0.15	1260	840	21	23	1590	0.336
17	Alloy VI-1	1.2	500	460	20	45	760	0.377
18	Alloy VI-2	0.8	780	720	13	42	1160	0.527
19	Alloy VI-3	0.65	1030	940	7.5	46	1590	0.794
20	Alloy VI-4	0.56	950	870	14.5	49	1510	0.829
	*Test temperature 673 K							

Table 1.6. *(Continued) Machinability coefficients and actual test data for the work materials*

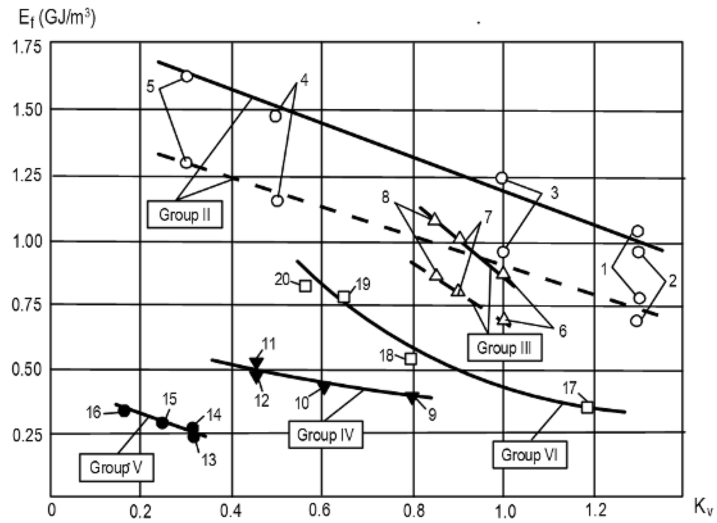

Figure 1.5. *Correlation of the proposed criterion with the experimental tool-life data – verification chart*

Accordingly, there is a continuing need to improve the machinability of titanium and titanium alloys. It has been proposed that the machinability of titanium and titanium alloys can be improved by adding one or more elements selected from S (sulfur), Se (selenium), Te (tellurium), REMs (rare earth metals) and Ca (calcium). These elements form inclusions in titanium or a titanium alloy and act to improve the machinability thereof. The amount of each free-cutting element which can be added is defined for the reasons described below. In the following description, all percentages given are, unless otherwise indicated, by weight.

Phosphorus (P)

Phosphorus is partly dissolved in Ti to form a solid solution and decrease the ductility of the matrix and the remaining part of phosphorus forms inclusions in Ti to improve the machinability. However, the addition of P alone causes a significant decrease in hot workability and fatigue strength. Therefore, P is added in combination with one or both of S and Ni, or with S, Ni and REMs. When the content of P is less than 0.01%, neither the amount of P dissolved in the Ti matrix nor the amount of inclusions formed is enough to attain an appreciable improvement in machinability. The addition of P in an amount greater than 1.0% causes the formation of coarse inclusions, resulting in a decrease in hot workability and fatigue strength, although the machinability is effectively improved. The balanced amount of P is present in an amount of 0.01−1.0%, preferably 0.03−0.30%.

Sulfur (S)

When sulfur is added along with P, it refines the inclusions formed by addition of P and minimizes the decrease in hot workability and fatigue strength caused thereby. The addition of less than 0.01% of S does not bring about an appreciable refinement of the inclusions so that the decrease in hot workability and fatigue strength cannot be suppressed adequately. When the content of S is greater than 1.0%, the inclusions are formed in an increased amount and many inclusions are present along the grain boundaries, thereby even resulting in a decrease in hot workability and fatigue strength. Therefore, when added, S is present in an amount of 0.01−1.0%, preferably 0.03−0.30%, and more preferably 0.08−0.24%.

When the weight ratio of S to P is within the range of 1:3 to 3:1, the effect of S on refinement of the inclusions is particularly significant and fine inclusions having an average diameter of 1 to 10 μm are formed. Thus, it is preferable that S be added in such an amount that the weight ratio of S:P be in the range of 1:3 to 3:1 and more preferably 1:2 to 2:1.

Nickel (Ni)

Nickel limits the size of the inclusions formed by addition of P and hence is effective for suppressing a decrease in hot workability and fatigue strength caused by addition of P. Furthermore, Ni forms an intermetallic compound with Ti, thereby improving the machinability. The addition of less than 0.01% Ni does not significantly improve the shape of the inclusions and therefore does not have an appreciable effect on suppression of a decrease in hot workability and fatigue strength. On the other hand, the addition of greater than 2.0% Ni causes the formation of a large amount of a Ti-Ni intermetallic compound, thereby decreasing the ductility and rather decreasing the hot workability and fatigue strength. Therefore, when added along with P, Ni is present in an amount of 0.01−2.0%, preferably 0.05−0.60%.

Rare earth metals (REMs)

Rare earth metals are reactive with P and serve to decrease the amount of P dissolved in the matrix, thereby lessening a decrease in ductility of the matrix and suppressing a decrease in hot workability and fatigue strength caused by addition of P. One or more REMs such as La (lanthanum), Ce (cerium), Nd (neodymium), Y (yttrium), Sc (scandium), etc. may be added in a total amount in the range of 0.01−5.0%, preferably 0.05−1.5%. Because REMs tend to increase the amount of inclusions, they are added along with S and Ni in addition to P in order to refine and make round-shaped inclusions.

The addition of an REM in an amount of less than 0.01% has little effect on alleviation of a decrease in ductility of the matrix and does not contribute to suppression of a decrease in hot workability and fatigue strength. The addition of an REM in an amount greater than 5.0% causes an increase in the viscosity of the molten Ti or Ti alloy in which the REM is dissolved and tends to cause an undesirable segregation. An REM can be added relatively inexpensively by using a commercially available mischmetal which is an alloy of REM predominantly comprising Ce, La, and Nd.

The free-machining Ti alloy may contain incidental impurities such as hydrogen (H) and nitrogen (N) and it is preferable that the total amount of these incidental impurities not be greater than 0.1%.

1.3.4.3.2. Heat treatment

Heat treatments are used if a composition of the work material allows a large range of mechanical properties to be obtained due to heat treatment. In considerations of machinability of the work material, a given heat treatment is useful when it results in reducing the energy needed for fracture of the layer being removed from the rest of the workpiece. An extra heat treatment for the enhancement of machinability is feasible when parts require extensive machining so the cost of additional heat treatment can be justified. On the other hand, however, for the parts that are not subjected to further heat treatment after machining, the additional heat treatment is carried out if it does not compromise the application-related mechanical/physical properties of machined parts.

Although many metallic materials used in industry, e.g. difficult-to-machine high nickel/chromium alloys and aluminum alloys, are heat treated for improvements in machinability, the heat treatment of carbon steels is most common as this group of materials constitute the most significant part of machined materials. The heat treatment of steel is the process of heating and cooling carbon steel to change the steel's physical and mechanical properties without changing the original shape and size. Heat treatment is often associated with increasing the strength of the steel, but it can also be used to alter certain manufacturing-related objectives such as improving machinability, formability, restore ductility, etc. Thus heat treatment is a very useful process in helping other manufacturing processes and also improving product performance by increasing strength, or it provides other desirable characteristics.

Steels with a carbon content from 0.25 percent to 0.65 percent are referred to as medium carbon steels. The response of these steels to heat treatment is much better than that of low carbon steels particularly when heat treatment for improving machinability is used. Depending on the response to heat treatment of this group of steels, medium carbon steel can be divided into two groups. The first group includes steels with 0.25–0.35 percent of carbon, whereas steels with 0.35–0.65 percent of carbon are included in the second group. Normalizing treatment is employed for improving the machinability of steels included into the first group, whereas the machinability of the second group of steels is improved by annealing. The optimal regime of both processes is selected to reduce the fracture energy of the work material.

In the consideration of the process machinability, the machinability criterion "minimizing the fracture energy of the work material" might not be sufficient in the consideration of the process machinability as the latter requires a much deeper look at the heat-treated structure of the work material. Heat treatment of medium carbon steels produces a mixed metallurgical structure of lamellar pearlite and spheroidite (spheroidite is a microstructure found in steel alloys consisting of sphere-like cementite particles within an α-ferrite matrix). Finding a suitable ferrite/pearlite ratio to achieve the highest machinability of a carbon steel is the goal. If the structure is not partially normalized, the strength and hardness may be too high for optimum machinability. In wrought steels with a carbon level higher than 0.55%, a completely spheroidized structure is preferred. Hardened and tempered structures are generally not desirable for machining.

Another problem with heat treatment for improving machinability is the possible formation of abrasive solid phases in the material metallurgical structure. In steels, the formation of cementite presents a problem due to the very low solubility of carbon in carbon forms of cementite as lamellar pearlite. Cementite, also known as iron carbide, is a chemical compound of iron and carbon, with the formula Fe_3C

(or Fe_2C:Fe). By weight, it is 6.67% carbon and 93.3% iron. It is a hard, brittle material, normally classified as a ceramic in its pure form. With increased amounts of carbon in steel, the content of cementite also increases. Cementite possesses a microhardness of, approximately, up to 1150 HV. Cementite lamellae spacing affects all mechanical properties including the machinability of the material; the finer the pearlite plate spacing, the harder the material and the shorter the tool life. Pearlite is a harder microstructure constituent than ferrite and generally causes higher (abrasive) tool wear. Higher carbon levels produce much finer, almost irresolvable pearlite.

A practical situation can occur when one applies heat treatment to enhance the machinability of a carbon steel; the cutting force and cutting temperature decrease while tool life becomes significantly lower. The former occurs due to minimizing the energy to fracture of the work material while the latter occurs due to the excessive amount of cementite after the applied heat treatment. This explains the statement made above that the process machinability requires a much deeper look at the metallurgical structure of the work material.

1.3.5. *Process machinability*

The process machinability is often dependant on machining economy rather than a physical criterion selected based upon a particular requirement for a given machining operation. As mentioned in the introduction to this chapter, the cutting speed corresponding to specific tool wear/tool life (e.g. 20 min), the magnitude of the cutting force, chip shape, roughness of machined surface, burr formation (drilling and milling), flatness, etc. can be selected as machinability criteria for a given operation. In such a selection, many variables are involved such as the type of machining operation (turning, drilling, milling, etc.), cutting tool material, tool design and geometry (standard vs. application-specific), workholding fixture design, machine capabilities/conditions, MWF (both properties and method of application), etc. Any of the listed variables can dramatically affect the process machinability under the selected machinability criterion. According to the author's experience, the process machinability, tool life, and cost per machined part can vary up to a factor of 20 depending on the optimality of a given machining operation. That is why the author has proposed to separate the notions of the material and process machinability.

On the other hand, the process machinability has a direct correlation with the work material machinability so this fact cannot be totally ignored. To assess this correlation, the process machinability for a given machining operation can be represented by the specific energy E_{pm} required by the machining system to carry out this machining operation. This energy can be calculated using the measured power consumed by the machine as

$$E_{pm} = \frac{60P_c}{MMR} \qquad [1.4]$$

where P_c is the cutting power (in W), MMR is the material removal rate (in mm^3/min), i.e. the volume of the work material removed per minute. For example, in longitudinal turning, MRR is calculated as

$$MRR = \pi a_p fn\left(d_w - a_p\right) \qquad [1.5]$$

where a_p is the depth of cut (in mm), f is the cutting feed (in mm/rev), n is the rotational speed (in rev/min), d_w is the diameter of the workpiece (in mm).

For modern machines with powerful digitally-controlled, truly high-speed motor-spindles, the cutting power can be directly measured and displayed by the machine controller as losses are negligible. For older machining systems with a powertrain, the cutting power is calculated as the difference between the working and idling powers.

1.3.5.1. *Assessment of machinability of various materials for a given operational condition*

The simplest use of the introduced process machinability criterion is for the determination of the machinability index for a given work material with respect to a specific reference material as suggested by Karpov [KAR 12]. The process machinability index K_{mp} is determined for given machining conditions as

$$K_{pm} = \frac{E_{pm-c}}{E_{pm-r}} \qquad [1.6]$$

where $E_{pm\text{-}c}$ is the specific cutting energy determined for a current work material and $E_{pm\text{-}r}$ is the specific cutting determined for the reference work material.

It is obvious that if $K_{mp} > 1$ then the machinability of the current work material is worse than that of the reference material; if $K_{mp} < 1$, the opposite is true; if $K_{mp} = 1$ then the current and the reference work materials have the same machinability. For example, for the following cutting conditions: operation – longitudinal turning; diameter of the workpiece D_w = 68 mm; length of the workpiece L_w = 160 mm; cutting tool geometry: tool cutting edge angle of the major cutting edge = tool cutting edge angle of the minor cutting edge = 45^o, normal rake angle γ_n = 0^o, normal clearance angle $\alpha_n = 10^o$, cutting edge inclination angle $\lambda_s = 0^o$, nose radius r_n = 1 mm; tool material – sintered carbide P20; cutting regime: rotational speed n = 630 rev/min, cutting feed f = 0.25 mm/rev, depth of cut a_p = 1 mm, the specific cutting energy determined the reference work material AISI 1045 was measured to be E_{pm-r} = 1.868 G/mm^3. For the same machining conditions, the specific cutting energy E_{pm-c} = 2335 G/mm^3 was determined for AISI steel 52100. Therefore, K_{pm} = 2.335/1.868 = 1.25.

1.3.5.2. *Assessment of machinability efficiency of the machining system – optimization of process machinability*

Nowadays the word *efficiency* is associated with process economy rather than with its physical nature thus using economy, e.g. cost-per-unit (part, hole, surface, etc.), dimensions. To distinguish between efficiency as a techno-economic term and as a physically-based entity, the term machinability efficiency will be used in further considerations. Machinability efficiency is not defined in the classical way as a ratio of the useful energy provided by the cutting system to the total energy required by this system. Instead, it is defined by the ratio of the above-defined work material efficiency to the process machinability, i.e.

$$e_m = \frac{E_f}{E_{pm}} \qquad [1.7]$$

It is obvious that not all the energy required by the cutting system (E_{pm}) is spent on the separation of the layer being removed; part of the energy spent in the cutting system dissipates in the components of the system (friction, deformation, heat) and in the environment [AST 06]. As a result, the cutting system consumes more energy than is necessary for the separation of the layer being removed. It is clear that the better the organization of the components of the cutting system, the smaller the difference between these two energies will be. On the other hand, the components of the machining system and the machining regime can be optimized to reduce process E_f.

A series of turning tests were carried out to verify the proposed notion of the process machinability and to reveal the influence of various parameters of the cutting system on this machinability. General purpose cutting inserts having the shape and tool material ISO SNMG 120404-QI GC4225 were selected for the test. A special tool holder was designed and made to provide these inserts with various rake angles. Figure 1.6 shows some representative results where the influence of the rake angle, cutting speed and feed in the machining of various work material – high carbon steel AISI 52100, medium carbon steel AISI 1045 and cast iron ASTM M48 class 30B – can be observed. As shown, the efficiency increases with the rake angle and the reduction of ductility of the work material. These results were anticipated because iof following the usual machining practice. A more pronounced effect of the rake angle is observed when the depth of cut, cutting speed and feed are increased.

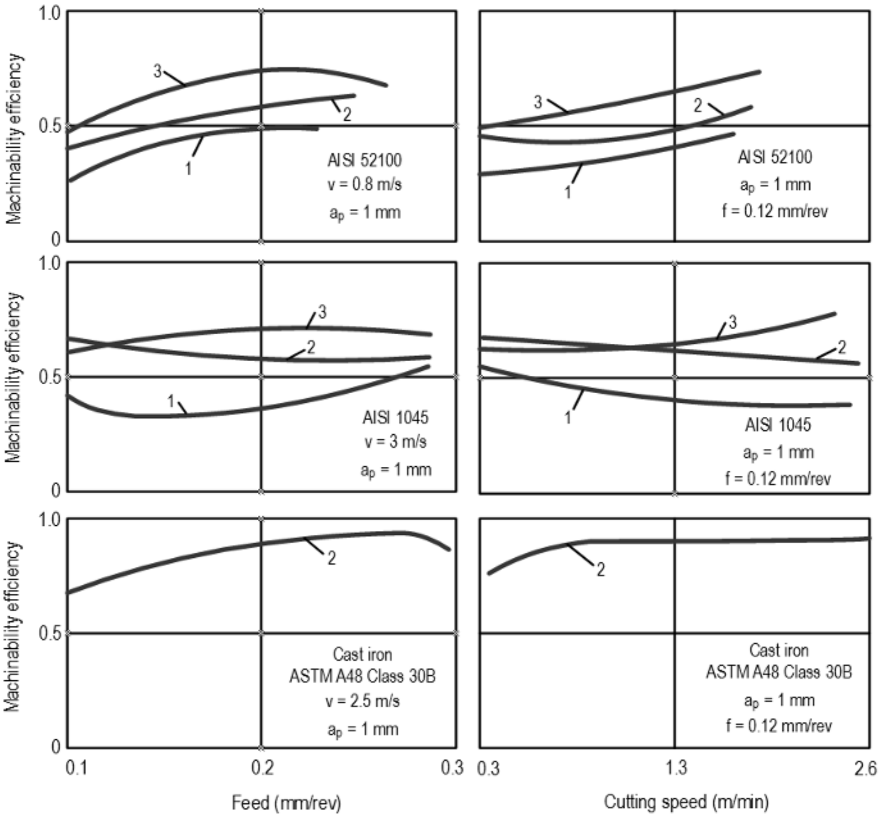

Figure 1.6. *Influence of the work material and process parameters on the machinability efficiency (1 – normal rake angle –10°; 2 – 0°; 3 – +10°)*

It follows from the test results and data presented in Figure 1.6 that the machinability efficiency depends to a large extent on the properties of the work material, i.e. on the work material machinability. For a wide range of commonly machined steels, machinability efficiency is in the range of 25–60%. This means that 40–75% of the energy consumed by the cutting system is required for the operation of the machining system. Most of this energy is spent on friction at the tool–chip and tool–workpiece interfaces. Naturally, this energy lowers tool life, affects the shape of the chip produced, and leads to the necessity of using different MWFs, which, in turn, lowers the efficiency of the machining system as more energy is required for MWF delivery and maintenance.

1.3.6. *Improvement the process machinability*

In metal cutting, the situation is entirely different compared to the design of tribological joints in modern machinery. In the latter, a designer is quite limited by the shape of the contacting surfaces, the materials used, the working conditions set by the outside operating requirements, the use of cooling and lubricating media, etc. In metal cutting, practically any parameters of the cutting system can be varied to a wide range. Modern machine tools do not limit a process designer with the selection of cutting speeds, feeds and depth of cut. The tool materials, geometry of cutting inserts and tool-holder nomenclature available at his or her disposal is very wide. The selection of MWF and its application techniques are practically unlimited. Although the chemical composition of the work material is normally given as set by the part designer, the properties of this material can be altered to a wide range by heat treatment, forging and casting conditions [AST 06]. Additional means of improving the process machinability such as, for example, pre-heating, pre-cooling and pre-deforming the workpiece as well introducing vibration to the tool/workpiece, can also be used in some specific applications. Table 1.7 lists some of the most useful methods.

Factors that increase E_{pm}	Factors that decrease E_{pm}
Decreased feed	Proper MWF application
Friction over the tool–chip interface	Favorable state of stress
Friction over the tool–workpiece interface	Pre-deforming of the surface of cut
Unfavorable state of stress	Pre-heating of the workpiece
Incorrect MWF application	Pre-cooling of the workpiece

Table 1.7. *Machinability factors*

The author’s analysis of the existing methods of enhancing the process machinability resulted in a stunning conclusion – any method of improving the process machinability works well when its application results in the reduction of the area under the damage curve of the work material (see Figure 1.4), i.e. when its application reduces the specific energy of the fracture of the layer being removed in machining. When specialists and researchers in machining understand the essence of this conclusion, they can efficiently apply multiple known methods of machinability encasement. Although the discussion of each particular method and its optimal implementation are the subjects of a separate, long overdue book, a brief discussion of some methods and their essence is given in this chapter.

1.3.6.1. *Tool geometry*

Surprisingly, a simple and powerful means to improve the process machinability is right in front of our eyes; everybody sees it, touches it, uses it on a daily basis, but does not know. This simple and powerful, but for many highly unclear, means to improve machinability is the cutting tool geometry. Although the basics of the tool geometry is covered in any book related to machining and the parameters of tool geometry are thoroughly defined in ISO and national standards (e.g. International Standard ISO 3002-1 :1982/Amd 1:1992 “Basic quantities in cutting and grinding. Part 1: Geometry of the active part of cutting tools - general terms, reference systems, tool and working angles, chip breakers” and American National Standard ANSI B94.50-1975 “Basic nomenclature and definitions for single-point cutting tools. 1975 (reaffirmed 1993)”), their influence on the cutting process/particular machining operation is not covered very well in the various literature sources on the subject. For example, the tool cutting edge angles of the major and minor cutting edges, the inclination angle of the cutting edge, and the tool nose radius are discussed only in the consideration of the “theoretical” roughness of the machining surface and, sometimes (in more scientific literature sources), the consideration of the uncut chip geometry parameters (e.g. the uncut chip thickness) while no relationships of these important parameters with the process machinability were revealed.

1.3.6.1.1. Rake angle influence

Among the many parameters of the cutting tool geometry, the rake angle somehow attracted more attention from the researchers and professionals. For example, Shaw [SHA 88] argued that the specific cutting energy (and thus the cutting force) decreases about 1% per degree of increase in the rake angle, Saglam, Yaldiz and Unsacar [SAG 07] showed that an increase in the rake angle noticeably reduces the cutting force while the cutting temperature increases. These and other multiple, similar findings became common knowledge in metal cutting and, as the properties of the tool materials improved, came to serve as the foundation of the development of modern cutting tools with a high rake angle showing exceptional performances compared to those with small rake angles [AST 10]. The question is, why does this happen? Why an increased rake angle reduces the cutting force and thus improves the process machinability remains unanswered. All attempts to explain the phenomenon as “it is clear that a sharper cutting tool works better” cannot be considered to be of a scientific nature. In other words, one of the oldest notions and a fact that is well proven experimentally has no physical/mechanical explanation. When it comes to finding physical/mechanical explanations or justifications for the selection of other parameters of the cutting tool geometry, the whole picture becomes even blurrier.

Surprisingly, the problem of explaining the influence of the rake angle and other parameters of the tool geometry can easily be explained, and thus the selection of these parameters together with the parameters of the machining regime (e.g. the feed and depth of cut) can be optimized if the definition of the metal cutting process presented in section 1.3.4.1 is used. According to this definition, the metal cutting process is essentially the purposeful fracture of the layer being removed. There are a number of further steps to understand what this definition actually implies.

The first step is to understand that fracture requires a certain multi-axial state of stress in the deformation zone as the major condition for fracture. One may argue, however, that fracture occurs in the tensile test although there is uniaxial loading in this test so there is no multi-axial stress. In reality, this is not quite so. Referring to the real damage curve shown in Figure 1.4, Figure 1.7 shows the schematic of the deformed and then fractured tensile specimen at different stages of loading. A little beyond point *b* on the damage curve (Figure 1.4) the material reaches its elastic limit. If strained beyond this point, it will not return to its original length when the stress is removed. It is now permanently strained and the material has entered the plastic region. If the stress is increased further, there will be a rapidly increasing strain up to point *d*, the ultimate tensile strength. This is the highest point on the curve and so the maximum stress to which the material can be subjected. At this point, the stress in the sample will suddenly decrease as the specimen rapidly stretches and will fail at point *f*. In fact what has happened is that the sample has "necked", a small section has stretched and narrowed (Figure 1.7), which increases the stress in the small volume of the neck, which in turn stretches further. Inside the neck, small gaps open up which rapidly combine into a single large void. The stress is now concentrated on a ring of material around the void which quickly tears open, failing at point *f*. A necked region in the tensile specimen is in effect a mild notch, causing a complex triaxial state of stress in that area. The material adjacent to the neck restrains its development. Radial and tangential stresses are thereby induced in addition to the axial stress. This triaxial state of stress causes fracture in the region of the neck as shown in Figure 1.7 [LIU 06].

One may argue, however, that no necking occurs in compression as the cutting tool compresses the layer being removed by its rake face so that plastic deformation by simple shearing occurs as accepted by the traditional theories of metal cutting [MER 45, SHA 04]. In reality, this is not quite so. Figure 1.8(a) shows a specimen made of a ductile material with a grid inscribed on its cylindrical surface. Figure 1.8(b) shows the grid distortion occurring in compression by the punch where simple shearing is the prime deformation. Note the barrel-like shape of the specimen before fracture. Such a phenomenon is known as barreling in compression and is the full equivalent to necking in tension. Once barreling occurs, the state of stress in the specimen becomes triaxial, which eventually leads to fracture as the load *P* increases.

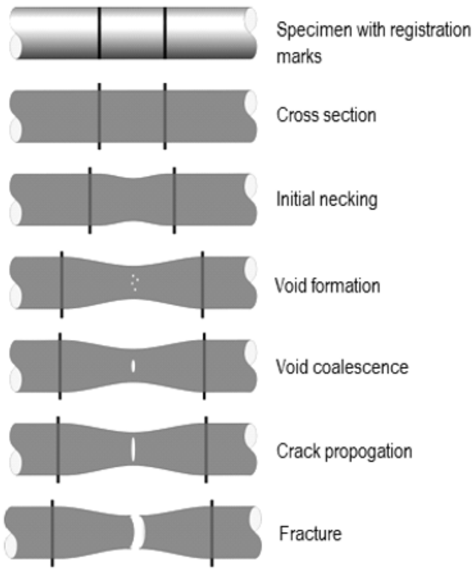

Figure 1.7. *Formation of the neck and fracture in tensile testing*

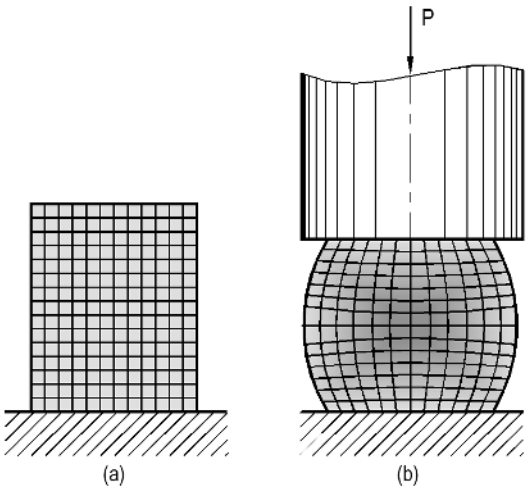

Figure 1.8. *Deformation pattern in compression: (a) specimen with the inscribed grid, (b) distortion of the initial grid*

Ductile materials are much weaker in shear than in tension or compression, thus failure of ductile materials is almost always caused by shearing. When shear stress is at a maximum, a ductile member could slide on 45º planes and create a cone-and-cup shaped fracture surface (tension Figure 1.7) or turn into a barrel-like shape (compression) with a crack running approximately 45º to the compression load as shown in Figure 1.9. In contrast, brittle materials are much stronger in shear than in tension or compression. Hence, brittle materials usually fail due to tension and compression. A tensile force causes the brittle member to break into two pieces, while a compressive force causes it to crack into a number of small fragments.

Figure 1.9. *Specimen made of VT20 titanium alloy fractures in compression testing*

Figure 1.10(a) shows grid distortion that occurs if the punch is shifted from the axis of the specimen to a position similar to that found in cutting. If one compares deformation patterns due to compression and cutting, a significant difference can be observed. At the initial stage of punch penetration, a deformation zone forms in front of the punch face due to the pure compression of the affected layer (analog of the layer to be removed in machining). As a result, the plastic deformation of this layer takes place by pure shearing during this stage. As the punch advances further, the plastically deformed part gradually comes into close contact with the punch face so a bump is formed in front of this face. As soon as the bump begins to form, the distortion of the initial grid does not resemble that found in pure (simple) shearing. This explains why simple shearing is not the prime deformation mode in metal cutting, as suggested by the single-shear plane and other known models of chip formation [SHA 04]. This simple fact is known from the mechanics of materials and could easily be confirmed by anyone conducting a simple test similar to that shown in Figure 1.10(a). Unfortunately, the known works on metal cutting do not account for this simple result.

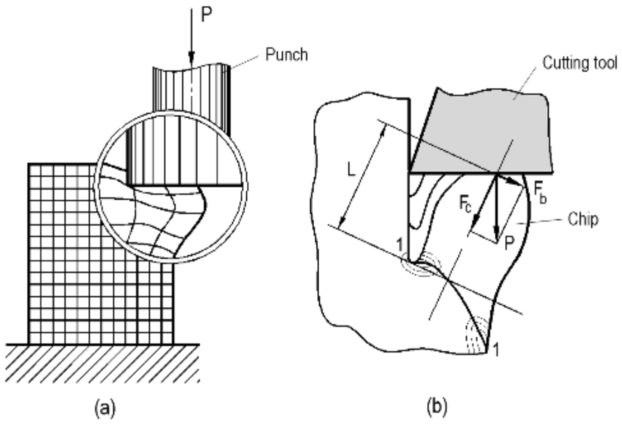

Figure 1.10. *Deformation pattern in cutting: (a) distortion of the initial grid, (b) interaction between the tool rake face and the partially formed chip*

As previously explained by the author [AST 10], any significant penetration of the punch shown in Figure 1.10(a) is impossible as the punch does not have the clearance angle. Once the clearance angle is applied to the deforming tool, it becomes a cutting tool. Figure 1.10(b) shows a simple model of the cutting tool (actually the punch with the clearance angle) penetration into the specimen considered as the workpiece. As shown, a partially formed chip forms in front of the tool that starts to slide over the tool rake face. This penetration force applied to the partially formed chip through the rake face of the tool can be resolved into two components, namely, compressive force F_c, acting along the direction of the conditional axis of the partially formed chip, and bending force F_b, acting along the transverse direction, as shown in Figure 1.10(b). Therefore, the partially formed chip is subjected to the mutual action of compression and bending (the bending moment $M = F_bL$). As a result, the state of stress in the chip root (where the chip connects to the rest of the workpiece through the elasto-plastic joint) becomes complex (triaxial) including a combination of the bending and compressive stresses. The complete model and its details have been previously discussed by the author [AST 06]. As a result of the discussed triaxiality, the purposeful fracture of the layer being removed takes place.

It could be argued, however, that the model shown in Figure 1.10(b) is only applicable for ductile materials, while the state of stress in brittle materials, and thus their fracture mode can be considerably different. To resolve this issue, the author would like to remind the reader that nobody has ever quantified the exact location of the border between the "Brittle/Ductile" regions in metal cutting, whereas in materials such a qualification is well defined. Whether a material is brittle or ductile could be a subjective guess, and often depends on temperature, strain levels, and other environmental conditions. However, a 5% elongation criterion at break is the accepted dividing line. Materials with a larger elongation can be considered ductile and those with a lower value brittle [FIS 09]. As a result, more that 95% of the work materials used are ductile as even cast irons that are considered in metal cutting as brittle have more than 7% elongation at fracture. As a result, work materials considered to be brittle in metal cutting exhibit substantial plastic deformation in chip formation before fracture as illustrated in the model shown in Figure 1.10(b). The mechanics of fracture in the cutting of brittle materials has been considered by the author previously [AST 98].

The recognition of the stress triaxiality in the deformation zone of metal cutting has opened up a breakthrough in the understanding and origination of process machinability, bringing true understanding to the nature of the metal cutting process. The essence of this breakthrough is that the same material will fail at different strain levels if tested under the uniaxial and multi-axial state of stress, as conclusively proven as early as 1911 by von Karman in his the pioneering experimental work on material testing [BON 97]. Works by Hancock and Mackenzie [HAN 76] and Thomson and Hancock [THO 84] extensively investigated the dependence of material ductility on the triaxiality state of stress showing the decay of material ductility as a function of triaxiality. Over the years, fracture mechanics researchers have made a tremendous effort in stress state parameterization and material characterization. Recently, Bai *et al.* [BAI 09] showed that the state of stress can be expressed in terms of the stress triaxiality state parameter η as

$$\eta = \frac{\sigma_m}{\bar{\sigma}} \qquad [1.8]$$

where σ_m is the mean stress, which represents the amount of pressure under which deformation takes place, and $\bar{\sigma}$ is the equivalent stress.

Figure 1.11 shows experimental results where a significant influence of the stress triaxiality on the fracture strain for steel AISI 1045 can be clearly seen [ABU 13]. In other words, the area under the damage curve for a given work material (Figure 1.4), taken as the criterion of the material machinability, can be altered to a wide extent by varying stress triaxiality. When it comes to improving the process machinability, this area should be minimized.

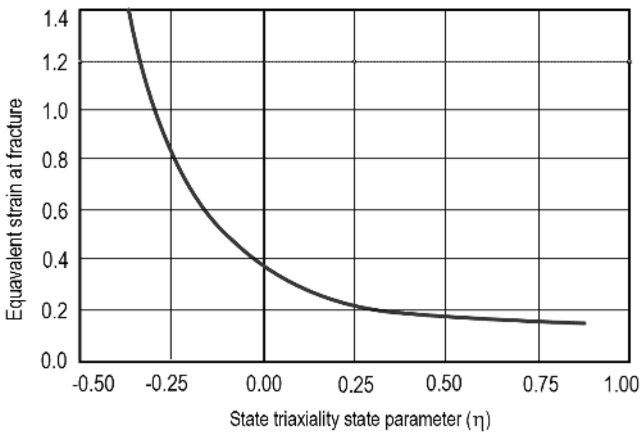

Figure 1.11. *Fracture locus obtained from DIC experiment in plane strain condition for steel AISI 1045*

Figure 1.12 shows a FEM confirmation of the results presented in Figure 1.11 [ABU 11]. It shows that the cutting of steel AISI 1045 with a high rake angle results in a much more preferable stress triaxiality in the chip formation zone so that the amount of plastic deformation of the layer being removed in its transformation into the chip is a lot smaller in machining with a 40^{o} rake angle compared to that with 0^{o} rake angle. This is because the strain at fracture in cutting with a high rake angle and thus the area under the damage curve (Figure 1.4) are much smaller according to Figure 1.11. Figure 1.13 shows an experimental comparison of chip deformations in the machining of steel 1045 with a 0^{o} and 10^{o} tool rake angle, providing a full experimental confirmation of the modeled results [ABU 13]. The reduction of this area results in a smaller cutting force, and thus a lower amount energy needed to remove the stock from the rest of the workpiece, so that the process machinability is improved.

1.3.6.1.2. Rake angle – practical considerations

Reading the previous section, one might argue, however, that a high positive rake angle is not very feasible in practical cutting as the cutting wedge (the part of the tool material between the rake and the flank faces of the tool) becomes weak so that it can apparently be fractured easily if some fluctuations of the cutting force occur. Such fluctuations traditionally occur due to tool/workpiece runout, misalignments in the machining system, lack of structural rigidity in this system and so on. It is instructive to explain that although the listed factors can be significant, the whole described notion of tool fracture is slightly outdated.

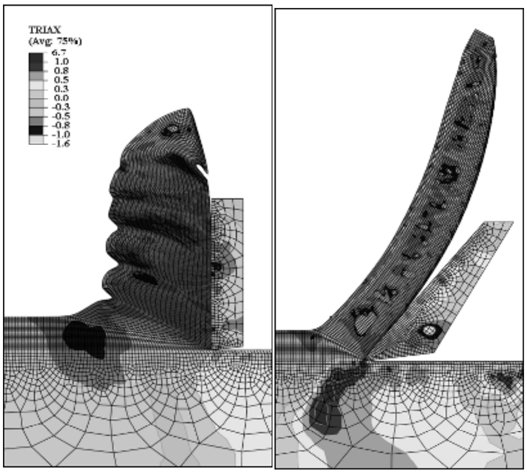

Figure 1.12. *Results of FEM of influence of the tool rake angle (0^o – left and 40^o – right) on stress triaxiality in the deformation zone in the machining of steel AISI 1045. For a color version of this figure, see www.iste.co.uk/davim/machinability.zip*

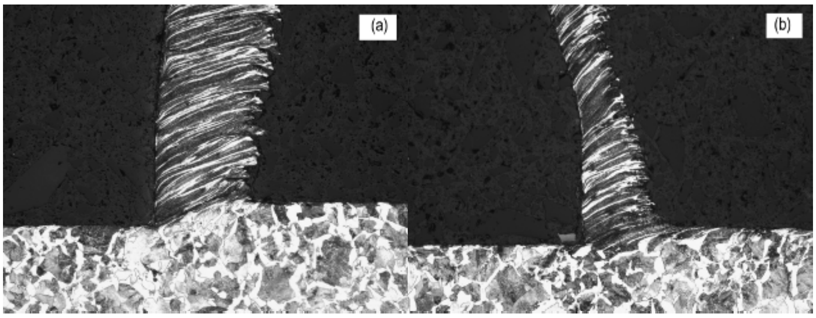

Figure 1.13. *Experimental comparison of chip deformation in the machining of steel 1045 with: (a) 0^o tool rake angle; (b) 10^o tool rake angle*

As discussed above, in the not-too-distant past, the components of the machining system were far from perfect in terms of assuring normal tool performance. Under these conditions, the use of cutting tools with high rake angles was impossible, particularly if such a tool was made of a "brittle" (for the described conditions) tool material such as, for example, a sintered carbide. Adjusting to these conditions, tool researchers and manufacturers developed "forgiving" carbide tools made of high-cobalt carbide grades and with negative rake angles. The price to be paid included low tool life and limited cutting speed and feed (productivity). For many years, a stable though fragile balance between inferior design/geometry cutting tools and poor machining system characteristics was maintained.

As discussed above, this has been rapidly changing since the beginning of the 21st Century. Modern sub-micrograin carbides possess sufficient fracture toughness. For many years, polycrystalline diamond (PCD) brazed and indexable cutting inserts were made with negative rake angles to cover up for imperfect machining systems. Due to the recent development of ultra-micrograin PCDs, advanced cutting tool manufacturers began to offer PCD inserts with high positive (up to 10^o) rake angles that significantly improve high-speed machining of high-silicon aluminum alloys widely used in the automotive industry (tool life, machined surface integrity, reduced cutting force, etc.). Unfortunately the available recommendations for the suitable tool geometries do not reflect the great advances made over last 5−10 years in the properties of tool materials and coatings.

Gradually, some tool manufacturers began to offer tools with extremely high rake angles primarily for the machining of aluminum alloys and copper. For example, Robertson Precision, Inc (Redwood City, California, USA) developed Shear Geometry® cutting tools with extremely high rake angles. Figure 1.14 shows an example of such tools and the chip formed in the machining of an aluminum alloy. The success of this tool became possible with the development of a special submicrograin sinter-HIPed carbide tool material.

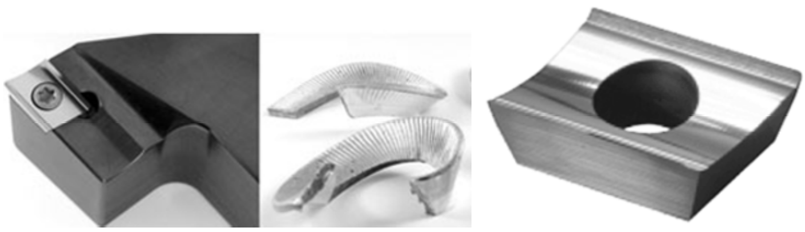

Figure 1.14. *Shear Geometry® cutting tool, formed chip and high-rake insert (Robertson Precision, Inc (Redwood City, CA))*

Nowadays, milling tools with high rake angles have become common. For example, Big Kaiser Precision Tooling Inc. (Elk Grove Village, Illinois, USA) offers a full-cut mill FCM type tool with 20^o rake angle. Allied Machine & Engineering Corporation (Dover, Ohio, USA) offers high rake geometry on its drills that is specifically designed to improve chip formation in materials with very high elasticity, extremely poor chip forming characteristics, and low material hardness. Leading tool manufacturers also offer high rake CCGT inserts (Figure 1.15) intended for non-ferrous materials instead of CCMT inserts. Practical machinists soon found that such inserts can cut practically anything. Although regular CCMT inserts often have a small positive rake angle, CCGT inserts offer much higher rake angles. The major insert manufacturers have special lines of this style of insert: ISCAR CCGT-AS, Kennametal CCGT-HP, Valenite CCGT-1L, Seco CCGT21.51F-ALKX, etc. Each has a slightly different sales pitch about why one should use the insert. ISCAR is pushing them as offering such a fine finish for aluminum that no grinding is needed, for example. Such inserts are recommended for various work materials crossing the previously-established lines between their machinability groups. What started out as an aluminum super finishing insert can now be found in formulations that extend to high temperature alloys, stainless steels, and other possibilities.

Figure 1.15. *A typical high rake CCGT insert*

1.3.6.1.3. Rake face shape and influence of other tool geometry parameters

For years, chipbreaking as an inherent part of process machinability was studied thoroughly [NAK 84, NAK 92]. Jawahir and Van Luttervelt [JAW 93], summarizing the 50-year effort into improving chipbreaking, showed that reliable chipbreaking can be achieved with 2D and 3D modifications of the tool rake face. Figure 1.16 shows the basic design of the chipbreaking step on the rake face, whereas Figure 1.17 shows the basic design of the chipbreaking groove made on the rake face. For many years, these basic chipbreaking means were studied to find the best parameters to achieve reliable chipbreaking for various groups of work material. Although it was noted that tool life (and thus process machinability) might decrease, increase or remain unchanged when a chipbreaker was applied, the studies concentrated on the conditions of breaking the chip in its root while no attention was paid to alterations in the state of stress in the deformation zone. In the author’s opinion, this alteration is the root cause of the discussed tool-life change. If, for example, the applied chipbreaker causes a more favorable state of stress in the deformation zone, then the process machinability increases.

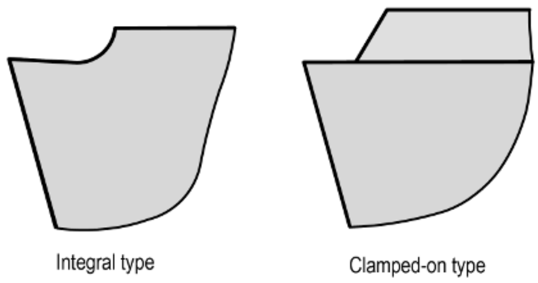

Figure 1.16. *Chipbreaking steps on the tool rake face*

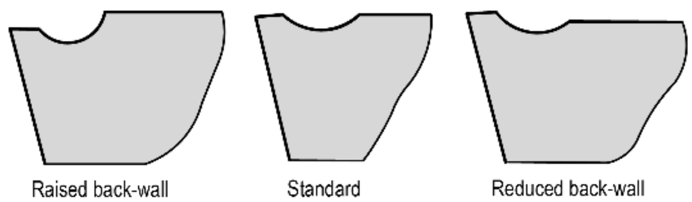

Figure 1.17. *Conventional chip groove*

Having noticed the change not only in chipbreaking conditions but also in process machinability, the manufacturers of cutting inserts designed thousands of different shapes for the tool rake face. Figure 1.18 shows several examples. It is interesting that the number of such designs combined with various coatings exceeds the number of not only groups but also the actual number of work materials used in industry. These shapes can significantly alter the state of stress in the deformation zone that can potentially improve the process machinability. Unfortunately, many of these shapes are developed with no clear understanding of why such an improvement occurs. It has not yet been realized that practically all major parameters of the cutting tool geometry combined with the contact properties of the tool material and parameters of the machining regime have a significant, yet not fully revealed, influence on the state of stress in the deformation zone, and thus on the process machinability. For example, ISCAR Co. has introduced extensions of the proven helical cutting edge concept into a wider range of cutting tool types and sizes, which has allowed a significant increase in the process machinability.

In the author's opinion, the major problem for researchers and tool developers in the field of metal cutting and tool design is that the influence of the tool geometry parameters on the state of stress (and thus the process machinability) are intertwined so it is impossible to study one parameter while paying little attention to the others. Only when a realistic FEM model of metal cutting is applied and the state of stress in the deformation zone is considered in the manner as discussed above, can the finding of the evaluation of the optimality of the insert geometry for a given application be carried out easily.

Figure 1.18. *Some designs of the rake face for modern cutting inserts*

1.3.6.2. *Preheating the workpiece*

The use of workpiece pre-heating (hot machining) as a technique for improving machining operations has been under consideration since the late 19^{th} Century [BAR 66]. Hot machining uses an external heat source(s) to soften the layer being removed in order to decrease its tensile strength and strain hardening [PEN 60]. The principle behind hot machining is increasing the difference in hardness of the cutting tool and workpiece, leading to a reduction in the component forces, an improved surface finish and a longer tool life [KRA 51]. Although there are a number of various techniques for pre-heating the work material, plasma-enhanced machining (known as PEM) and laser-assisted machining (known as LAM) have been intensively studied since the mid-20th Century and have some practical implementations in industry.

In PEM, the layer being removed is subjected to intense localized beating using a plasma torch directed to the surface to be machined (the work surface) ahead of the cutting tool. The output of the plasma torch is set such that the temperature of the layer being removed by the cutting tool is raised to a level at which the strength of the work material is reduced to enable the tool to cut satisfactorily. Argon is used as a plasma forming gas. Despite the number of advantages offered by traditional PEM, including its simplicity and high density of heat flux, its efficiency is limited by the low thermoconductivity of the high alloys. As a result, the depth of cut and feed rate should be lowered, decreasing the machining operation efficiency. Moreover, in roughing operations where this machining method should show the maximum efficiency, the casting skin of high alloys is often loaded with non-metallic inclusions whose strength properties remain unchanged with heating.

In advanced PEM, the plasma torch is positioned ahead of the cutting tool so the plasma jet heats the transient surface instead of the work surface as in the traditional PEM [ÖZE 01] as shown in Figure 1.19. Depending on the properties of the work material, feed *f*, cutting speed *v*, depth of cut, and the operating mode of the plasma torch, the angle α between the direction of the cutting speed and the axis of the plasma jet ranges from 0^o to 45^o while the angle β between the axis of the plasma jet and the direction of feed is ranges from 10^o to 45^o. The arc distance *H* between the tool cutting edge and the intersection point of the axis of the plasma jet with the transient surface is selected as a function of the cutting speed and the intensity of the plasma torch to deliver the optimal temperature of the layer being removed in the deformation zone caused by the cutting edge.

The same as PEM, LAM is based upon the idea that the strength of materials generally decreases at elevated temperatures. This technique has been in use since the late 1970s when lasers became a viable heat source capable of producing intense heat in a very precise region. Laser-assisted machining typically involves using a high power laser as a heat source to soften the workpiece material ahead of a cutting tool in a lathe or milling machine, for example, to facilitate material removal and prolong tool life. Due to inefficiencies associated with laser−metal interactions and high initial startup costs (for example, a 1.5 KW CO_2 laser costs more than \$150,000), economic justification for laser-assisted machining of metals was not achieved. However, continued improvements in lasers, such as higher power Nd:Yag lasers and solid-state diode lasers, have provided the potential for improvements in the laser-assisted machining of metals.

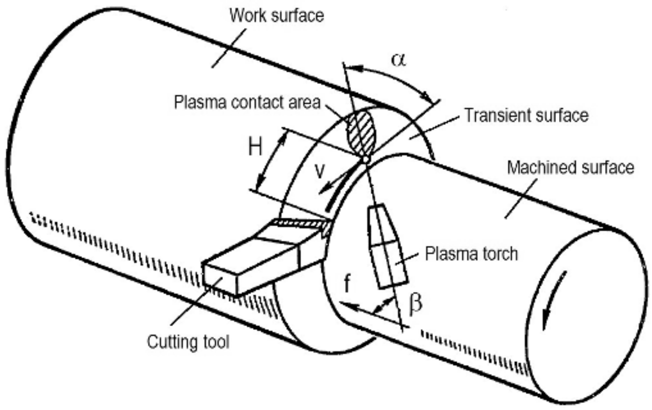

Figure 1.19. *The schematic for advanced PEM*

Figure 1.20 shows the schematic of one possible arrangement of LAM (US Patent No. 8,053,705, 2011). Two laser units are strategically positioned around a workpiece so that a desired temperature distribution that assists in the removal of material can be created within the workpiece. One laser beam heats the transient surface of the workpiece prior to the cutting tool, whereas the second laser heats the work surface. As a result, these two laser beams provide sequential incremental heating from different directions and positions such that only the material zone to be removed reaches the temperature conducive to machining, while the remaining bulk material is relatively unaffected. Furthermore, sequential heating can generate surface treatment effects, which can improve absorptivity for the following laser beams, thereby significantly improving energy efficiency for the laser-assisted machining of materials with high reflectivity such as metals.

In the author's opinion, the rather limited application of the discussed technique of machinability improvement is due to the lack of understanding of the physics behind this technique and thus the optimal regimes of pre-heating for a given application. Normally, the pre-heating temperature is studied for given conditions to achieve the highest tool life while not bringing unwanted structural changes to the machined surface. This temperature is measured by different authors in different places while the temperature of deformation in machining is not considered. The great variety of locations of plasma torches and lasers, various groups of machined materials, machining operations, cutting regimes, tools and tool geometries, etc. used, make it next to impossible to make any generalization about the results in terms of recommending the optimal parameters of hot machining for given conditions.

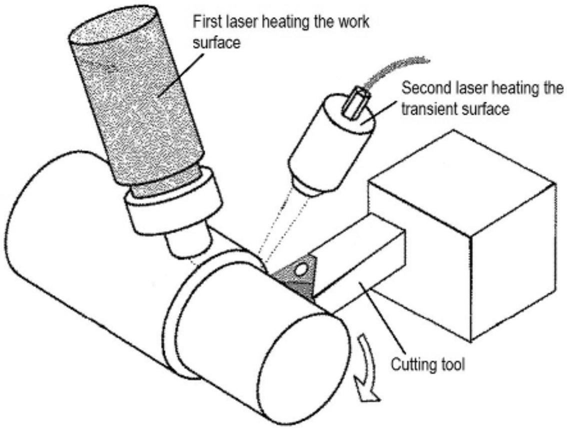

Figure 1.20. *Schematic of LAM*

The study of hot machining by Talantov [TAL 88] can be considered as a good example. He studied the influence of the furnace method of pre-heating of workpiece on machinability of titanium alloy BT6 and found that all the power components of the cutting force decreases with the increase in the pre-heating temperature to a certain temperature whereas the radial and the axial components sharply increase to their peak values at this temperature. This temperature was called the optimal pre-heating temperature for the investigated titanium alloy. Using an average flank wear of 0.3 mm as the tool-life criterion, tool life at the optimal pre-heating temperature increases to 3,000 s of machining time compared to 160 s at room temperature. Talantov attributed this increase in the length of the tool–chip interface (1 mm at the optimum pre-heating temperature vs. 0.5 mm at room temperature) to a significant reduction of the normal stresses over the tool–chip interface. The author’s analysis of the Talantov’s data showed that the stress at fracture for the investigated titanium alloy decreased almost three times while the strain at fracture increased only by 40%. As a result, the area under the damage curve of the work material was significantly reduced. This is the physical essence of the obtained improvement whereas the increased tool-chip contact length is only an “internal” manifestation of the discussed improvement.

In the author’s opinion, any attempt to apply the hot machining should include the following steps:

– The optimal temperature of pre-heating of the layer being removed in the deformation zone (just in front of the tool cutting edge) should be clearly defined. As such, the properties of a given work material at elevated temperatures should be considered. Table 1.8 shows some basic examples. As can be seen, the optimal pre-heating temperature depends on both stress and strain at fracture of the work material so it is selected to ensure the minimum possible area under the damage curve. For example, for steels AISI 1010 this temperature is 350°C, for AISI 1045 it is 300°C, and for AISI 421 it is 600°C.

Temperature (°C)	Tensile strength Rm (MPa)	Elongation at break A5 (%)	Reduction of area AR (%)
	Low carbon steel AISI 1010 (normalized at 900-920°C)		
20	420	32	69
200	485	20	55
300	516	23	55
400	355	24	70
500	256	19	63
Medium carbon steel AISI 1045			
20	690	20	36
200	710	22	44
300	560	21	65
400	370	23	67
500	215	33	90
Austenitic stainless steel AISI 321 (quenching 1050°C, water)			
20	620	41	63
300	460	31	65
400	450	31	65
500	450	29	65
600	400	25	61
700	280	26	59
800	180	35	69

Table 1.8. *Mechanical properties of some work materials at room and elevated temperatures. Note that ductility of the listed work material decreases at elevated temperatures*

– The location of the plasma torch, laser, or induction coil should be selected based on “real estate” available in a particular machine/partholding fixture and tool location/clamping. The workpiece can also be pre-heated in a furnace so its handling and clamping procedures should be developed.

– Defining the parameters of pre-heating to assure the optimal cutting temperature depending on a particular arrangement of the machining setup and machining regime. Ideally, the inverse heat conduction problem should be solved to determine plasma parameters, laser power, or temperature of the workpiece pre-heating in the furnace.

Unfortunately, the author is unaware of anyone in the research and application of hot machining who has followed these steps.

1.3.6.3. *Advanced plastic deformation (APD) of the work material*

Cutting with APD includes a combination of two processes − surface plastic deformation, creating the necessary depth and extent of cold-working, and the consequent removal of the hardened layer by the cutting tool. A simple schematic of the machining with APD is shown in Figure 1.21 where the basic essentials of the process are indicated. As can be seen, a roller is pressed against the transient surface (the surface of cut) of the workpiece by a certain force P_c thus creating the contact stress q_c over the roller-transient surface interfaces. As a result, a certain cold-working in the layer being removed by the cutting tool is achieved so less energy of the plastic deformation is spent in actual cutting.

Figure 1.22 shows the essence of the process. As shown, the area under the damage curve that represents the energy needed for fracture of the unit volume of the work material includes two distinctive regions. The first is the energy spent in cold-working by the roller (area under curve abc) and the second is the energy spent in cutting (area under curve cdef). As can be seen, the latter is much smaller than the total area under the damage curve (see Figure 1.4) so that the process machinability is improved.

Analyzing Figure 1.22, one can conclude that the process is efficient in the machining of highly ductile materials such as, for example, austenitic stainless steels not having a high strength but great strain at fracture. A detailed investigation of the application of the process in the longitudinal turning of steel AISI 321 with a carbide tool resulted in the following [POL 11]:

− improved tool life by 25–60% depending on the optimality of the selected regimes (both cutting and APD);

− significant improvement in surface roughness;

– preventing the barreling of the workpiece due to high radial force that allowed an increase of the feed by 30%;

– significant improvement in chip breakability.

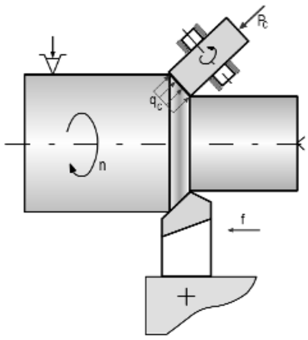

Figure 1.21. *Schematic of the machining with APD*

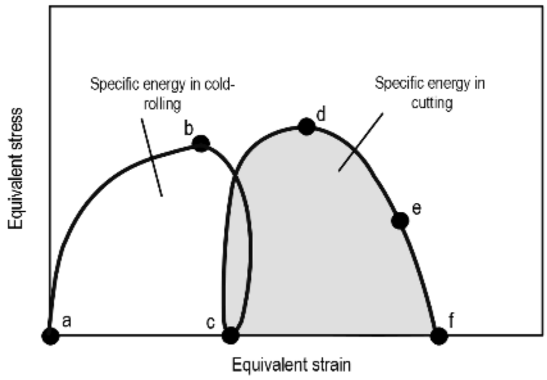

Figure 1.22. *Modified damage curve for the machining with APD*

The optimal regime of APD is thought of as the optimal contact stress q_c over the roller-transient surface interfaces (see Figure 1.21). It should be selected so that the depth of cold-working of the transient surface exceeds the uncut chip thickness. There is an optimal depth of such cold-working when the process machinability is the best in terms of increasing tool life, improving machined surface integrity and diametric accuracy as well as providing maximum enhancement to chip breakability.

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