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ORIGINAL ARTICLE

A review on the machining of cast irons

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Abstract Nowadays, the search for new materials is concerning to reduce the relative "efficiency/weight" ratio and its costs, in general, in the whole manufacturing chain, since the design until the final manufacturing stage. The efforts to achieve these requirements must fall in one of two options: (i) selecting "new" materials with similar strength of the "old," but with low density or (ii) increasing the strength of the existing materials by adding alloying elements or by heat treatment. Choosing the best material for a given application depends on a few parameters such as mechanical loads, thermal environments, manufacturing costs, recycling, public acceptance, and workability. Among several kinds of materials are the cast irons, which almost always provide good machinability and low production cost. Under the scenario of the Industrial Revolution to date, cast iron received great emphasis on its development from the point of view of its properties and economic advantages. Currently, among the metallic materials, cast irons are the second most produced, after steels. They are an extremely important group of metal for the industry because, by introducing alloying elements and applying appropriate heat treatment, their use has become viable in some applications that were exclusively of steels. The several grades and groups available, on the other hand, brings another concern about their machinability. After production on the foundry, cast irons always are processed by machining, involving a large amount of money. With the goal of bringing relevant information on the machinability characteristics of cast irons, this review was produced. It covers the main output parameters in machining (forces and power consumption, cutting temperature, surface roughness, recommended cutting tools, tool wear, and corresponding use of computational modeling technique, by using the finite element method) finalizing with future trends. It is hoped to fill a gap in the literature for those involved with machinability of this important metal.

Keywords Machinability · Cast iron, cutting force, and power consumption · Cutting temperature · Surface roughness · Tool material for machining cast iron

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1 Introduction

Cast irons and steels are the materials most used by the industry and in many sectors, not only because of its inherent characteristics but also its immense versatility [27]. According to the 44th World Casting Census, graphitic cast iron constitute 71% of the total metal casting in the world, followed by 17% of nonferrous casting and 9% of steel casting [26]. The developing research on cast irons contributed to pose this material in great competition with steel [49]. Such developments, resulting from needs in the areas of application or even cost reduction, bring as a consequence the technological updating of this old traditional material [52]. Knowledge of cutting forces, chip morphology, temperatures, surface roughness, residual stresses and surface integrity, etc., is an important prerequisite for reducing machining costs and improving product quality [19, 125].

As one advantage of cast irons is the possibility of obtaining parts with complex shapes. The combustion engine block and head, for instance, illustrates the details and shapes that can be obtained with the casting process, which is characterized as the most economic way for manufacturing parts with complex geometry. As one disadvantage is regarding its high density and consequently production of heavy components and thus, reduction of weight is a great challenge for the engineers and metallurgists. Alloying elements and heat treatments are options to improve cast iron properties, which in turn impact in the machinability. The manufacturing tolerances specified in projects cannot be obtained directly from the casting process; hence, the machining is employed for specific function, improve surface finish and dimensional accuracy of the castings [101].

The cast iron may have different mechanical properties depending on the alloying elements present or heat treatment undergone [51, 54]. The microstructures also play significant hole and affect the physical and mechanical properties of these materials, mainly when there is presence of pure graphite [96, 131]. The pure graphite has negligible resistance and provides a self-lubricating source at the cutting edge during machining [23, 46, 51].

Cast irons are a class of ferrous alloys having carbon contents above 2.1% (wt); however, in practice, many cast irons contain between 3.0 and 4.5% (wt) of carbon plus the addition of other alloying elements [13]. Cast irons are Fe/C/Si alloys, further containing Mn, S, and P, and may additionally have various other alloying elements [51]. Other authors, like Chiaverini [18], defines iron as "iron-carbon-silicon alloy with carbon contents above of 2%, in an amount greater than that which is retained in solid solution in austenite, to produce carbon partially free, as graphite flakes or lamellae."

The major application of cast irons is in automotive industry (brake drums and disks, exhaust manifolds, cylinder heads, and especially engine blocks, including diesel engines) and obviously gives rise to the need for further improvement in research and innovation, which aims to better understand the performance of these materials before the various types of fabrication processes [11]. Basement for machine tools, parts of highway machines (articulated trucks, dozer blades, draglines, compactors, asphalt pavers, etc.), pumps for miner industries, among others, are applications of diverses types of cast iron. Increased resistance in the cast iron is driven mainly by the most demanding performance requirements in engine vehicles, together with increasingly stringent environmental standards regarding emissions and fuel consumption [87]. Bearing investments in research and developing new products in this line become a very important factor in the economy in general.

2 Characteristics and properties of cast iron

Cast irons are classified into different families, especially according to the graphite. The name of each family reflects the form of the graphite (nodular, vermicular) or is related to the appearance of the fracture (gray, white), or even with some important mechanical property (malleable) [20, 51, 123]. Definitions of each type of cast iron are as follows [18]:

White cast irons—are those where all of the carbon present in the alloy is in the form of cementite or other carbides. The sequence of solidification and microstructure of these materials can be interpreted by the metastable equilibrium diagram (Fe/Fe_3C), with modifications necessary due to the presence of other chemical elements. This type of iron is, therefore, very hard and its machinability is strongly dependent on its microstructure. Kosasu et al. [76] studied the influence of the microhardness and microstructure of high chromium white cast iron on the machining performance in terms of tool wear and tool life, cutting forces, and surface quality using cBN tools. The variation of microhardness was determined by a grid nano-indentation approach. Volume fraction phases of the material were identified through Weibull mixture distribution from the result of the grid nano-indentation. High chromium white cast irons were prepared with two groups of composition, low carbon/silicon and high carbon/silicon, in the state of as-cast and hardened conditions. Results from the machining tests indicated that the variation of microhardness of the work materials showed significant impacts on the cutting tool wear, tool life, cutting forces, and surface quality of these materials.

Gray cast irons—are those that the phase formed during solidification are the austenite and graphite, following the stable equilibrium diagram. In these alloys, graphite is obtained in the form of flakes or lamellae, being necessary to distinguish from the combined carbon content, whose sum gives the total carbon content of these cast irons. Different microstructures can be obtained by adjusting the composition and/or by using an appropriate heat treatment [13]. For example, lowering the silicon content or increasing the cooling rate can prevent complete dissociation of the cementite to form graphite. Under these circumstances, the microstructure consists of graphite flakes embedded in a pearlite matrix.

Nodular cast irons—are those in which the graphite has the form of nodules (or spheroids in the melted material) due to the addition of chemical elements or individual manufacturing conditions, which modify the physical form of the graphite with no formation of lamellae as in the gray cast iron. The nodular form of the graphite is obtained from the addition of elements such as Mg and

Ni. In contrast, other elements such as Pb and Ti act as anti-nodulizing [96].

Malleable cast irons—are alloys that solidify as white cast irons, being subsequently subjected to an annealing heat treatment, when the brittle structure from first cast is transformed into the malleable form, where the cementite is decomposed into graphite and austenite and then is partially removed by oxidation with formation of some graphites.

Compact graphite cast irons (*CGI*)—are more modern material. In them, it is possible to obtain the crude molten state, by adding alloying elements, the so-called vermicular graphite, which is an intermediate form between flakes and nodules. According to Santos [112], the material from the point of view of the chemical composition range shows no significant difference from gray and nodular cast irons (each containing about 94% iron, 3% carbon, 2.5% silicon, and the remainder is divided among alloying elements and residual elements). The main differences between these alloys are due to their types of graphite morphologies, which confer different physical and mechanical properties to each. The process of obtaining the vermicular graphite is by means of the magnesium action, which is a nodulizing element, present in a range of 0.01 to 0.02% [33, 54, 93, 99]. In this type of cast iron the graphite are elongated and randomly oriented, as in gray cast iron; however, their graphite are shorter and thicker as compared with the lamellar graphite, besides having the rounded ends [2].

Due to its chemical composition, kinds, shapes, and distribution of phases, the machined surfaces of cast irons normally have the matte aspect, which compromise its finishing and consequently its machinability [32]. During machining, there is the environmental pollution with graphite particles, requiring, therefore, breathing filters to protect the operator and neighbor workers [84]. Besides graphite, SiC Fe_3C and other precipitates can also be pulled out, depending on the king of cast iron, which can penetrate between into the mobile parts of the machine tool, acting as abrasive particles, hence, increasing substantially the wear of sliders, gears, shafts, etc. reducing its life [127]. The graphite powders can also penetrate in the electric commands of the machine tools, if they are not well protected, and promote short-circuits.

The elements that most influence the microstructure of cast iron are carbon (determines the amount of graphite that may be formed) and silicon (graphitizing element, favoring therefore decomposition of iron carbide). The presence of silicon, independent of the carbon content, can make a cast iron to tend to gray or white [107]. Manganese, when present, has the opposite effect to that of silicon, i.e., stabilizes the cementite and thus counteracts the graphitizing action of the silicon [29]. The other elements (normal impurities and sulfur, for instance) have no significant actions from the point of view of graphitizing trend; however, only the phosphorus is relatively strong iron carbide stabilizer. Its main function is in the structure of the material, forming with the iron and carbon a compound of eutectic nature (iron carbide and iron phosphide) of white and perforated appearance named "steadite" [18]. Table 1 shows the effect of some chemical elements present in the molten iron on the microstructure of the final product.

The metal matrix of cast irons can be constituted by ferrite (microconstituent, which results in higher ductility and toughness) or pearlite (implies good mechanical strength associated with low ductility). Higher strength can be achieved with tempered martensite or ausferrite [51].

The mechanical and physical properties (strength, ductility, Young modulus, thermal conductivity, and damping capacity) are strongly dependent on the structure and distribution of the microstructural constituents [43, 44]. The addition of alloying elements provides changes to the cast iron microstructure, causing it to have an average increase of 20 to 25% in strength and hardness, and a rise of 5 to 10% in Young modulus and fatigue resistance [18, 64]. The inoculation, for example, by adding an alloying element (most commonly silicon) in the metal when it is still in the liquid state in the furnace, strongly affects the formation of graphite in the cast iron, thus increasing the tendency towards graphitization [33], as seen previously.

Ryntz and Arnson [108] studied the effect of bonded iron-silicon inserts on hardness control in cast irons and identified that hardness control should provide improved machinability. Janowak and Gundlach [63] conducted machinability tests in two grades of 45C high strength gray cast irons, containing nominally 0.1 and 3% of intercellular carbides and found that 3% of intercellular carbides substantially reduced tool lives. Likewise, eliminating the carbides increased tool lives up to 300% and for a fixed tool life of 1 h, the cutting speed could be increased by 41%. Bates [6] examined the influence of the mass fraction of microcarbides on the machinability of cast irons. The formation of microcarbides was controlled during casting by monitoring the cooling rate from the eutectic temperature to the eutectoid temperature, and by controlling the concentration of pearlite stabilizing elements. The results indicated that the mass fraction of microcarbides is the main factor influencing the machinability of gray and ductile cast irons Eleftheriou and Bates [36] studied the machinability of grade 40 of gray cast iron inoculated by three inoculant types: 0.2% additions of Sr bearing of 50% FeSi; 0.2% additions of 75% FeSi containing Ca and Al; and 0.2% additions of 40% FeSi containing Ce. The results showed that the gray casting iron inoculated with Sr-bearing FeSi at a drill speed below 100 sfm (surface feet per minute) presented the best machinability.

The white cast iron has a clear appearance due to the absence of graphite, since almost all the carbon is in the form of

Table 1 Effects of some structural elements in cast irons [18]

Chemical element	Effect during solidification	Effect during the eutectoid reaction
Aluminum	Hard graphitizing	Promote the ferrite and graphite formation
Antimony	Little effect	Strong stabilizing for pearlite
Boron (up to 0, 15%)	Hard graphitizing	Promote the graphite formation
Boron (above of 0, 15%)	Carbide stabilizing	Strong trend to retained the pearlite
Chromium	Strong trend to carburizing	Strong trend of pearlite formation
Copper	Weak graphitizing	Promote the pearlite action
Manganese	Weak trend to carburizing	Strong promoter of the pearlite formation
Molybdenum	Weak trend to carburizing	Strong promoter of the pearlite formation
Nickel	Graphitizing	Weak promoter of the pearlite formation
Silicon	Strong graphitizing	Promote the ferrite and graphite formation
Tellurium	Strong trend to carburizing	Weak pearlite stabilization
Tin	Little effect	Strong trend of the retained pearlite
Titanium (up to 0, 25%)	Graphitizing	Promote the graphite action
Vanadium	Strong trend to carburizing	Strong pearlite formation

carbide. This material is extremely hard and wear resistant, however, is brittle and difficult to machine, even with the best tools [92].

The properties of gray cast iron are influenced by the size, shape, and distribution of the graphite and by the relative hardness of the metal matrix that surrounds the graphite. Mechanically, cast irons are comparatively brittle as a consequence of their microstructure [23]. The tips of the graphite flakes are sharp and focused and can serve as stress concentration points when an external force of tensile is applied; however, its mechanical strength and ductility are much greater for compressive loads [58]. In addition, the gray cast irons exhibit high wear resistance. Furthermore, in the liquid melt state, they have high fluidity (allowing casting of parts with intricate shapes) and low melting contraction [13]. Figure 1 compares the damping capacity of steels and cast irons. Note that the gray cast irons have better efficiency in energy vibrational damping (important feature in machine tools, for instance) [92].

The gray cast irons cover a tensile strength range of 100 to 400 MPa (most commonly 150 to 300 MPa) and elongation, being very small is not specified. The graphite in the form of flakes guarantees good thermal conductivity, which makes gray cast iron a material widely used in components subject to thermal fatigue (drums and brake discs, engine blocks and heads, for instance) [8, 51].

Baohong et al. [4] showed that gray cast iron treated with 60%FeSi75 + 40% RE inoculants (wt% of 41.1 of Si, 0.35 of Al, 0.96 of Ca, 0.33 of Mn, 0.44 of P, 0.08 of Ti, 9.08 of Ce and the rest of Fe) exhibited consistent tensile strength at about 295 MPa along with good hardness and improved metallurgical quality. On the other hand, gray cast iron inoculated with 20%FeSi75 + 80% Sr inoculants exhibited the best machinability, the lowest cross section sensibility, and the least microhardness difference. The tool flank wear of the drill increased correspondingly with the increase of the microhardness difference of the matrix, indicating the great effect of the homogeneity of the matrix on the machinability of gray cast irons.

Xue and Li [142] investigated the effects of the inoculants on gray cat irons. The properties of the graphite morphology, matrix structure, mechanical properties, and fracture characteristics of the gray cast irons were examined. The results show that both the new inoculant X (mainly contains SiC) and the conventional inoculant FeSi75 resulted in improved properties of the molten iron over the original uninoculated molten iron. The inoculants produced smaller graphite particles, reduced tendency to form shrinkage cavities and porosities during the solidification of the molten iron, decreased supercooling degree, reduced formation of non-metal inclusions, and enhanced mechanical properties (of the cast irons).

The nodular cast irons have had large technical developments which have resulted in new business opportunities for

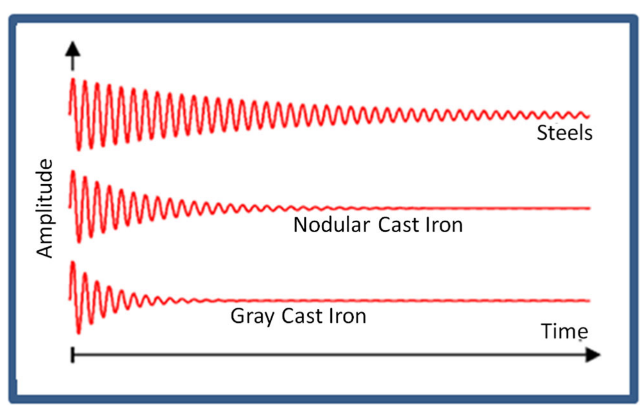


Fig. 1 Comparison of vibration damping capacity. Adapted from MSPC [92]

the foundry industry [134]. These materials offer a range of properties which are not found in other cast iron such as high strength, wear resistance, fatigue resistance, ductility, and toughness [143]. According to Oliveira [96], nodular cast irons exhibit lower stress concentration when compared to other castings, due to the graphite form of nodules (spheroidal), thereby maintaining the continuity of the matrix. Due to these versatile properties, these materials have taken much of the market for low-strength steels, making it suitable for the manufacture of crankshaft, pistons, gears, tubes, and dies [112, 133, 143]. When needing nodular cast iron with better mechanical strength and hardness than that found normally, two approaches are used: increase the proportion of cementite (this procedure reduces toughness making the material susceptible to cracking) and/or increase the content of carbides (this can affect the balance of graphite/carbides) [131].

Malleable cast irons are the first family of castings with significant ductility. They are always obtained by heat treatment, which may be of graphitization (black malleable iron) or decarburization (white soft iron). In black malleable cast iron, the graphite is in the form of aggregates and the matrix may be ferritic, pearlitic, or tempered martensite, covering grades with tensile strength ranging from 300 to 700 MPa and elongation from 2 to 12% [53]. Malleable cast irons were, for the most applications, replaced by nodular cast iron, with technical and economic advantages. In America and Europe, large applications are in tubes, curves, and connections for fluid transportation (miner industries, for example), in white or black malleable cast iron, with ferritic matrix [51]. In general, the microstructure of this material is similar to that of a nodular cast iron, which explains the high mechanical strength and significant ductility and malleability [13].

The compact graphite cast iron (CGI) exhibits mechanical strength, ductility, and toughness greater than gray cast irons; however, its thermal conductivity, vibration absorption capacity, and workability are inferior [24, 55]. Guesser [50] states that the CGI combines the good properties of gray and nodular cast irons. According to Sahm et al. [109], CGI, for example, is 33% more abrasive and 15% less adhesive than gray cast iron. While lamellar graphite, whose surfaces have fewer irregularities as compared to vermicular graphites, promotes the initiation and propagation of fractures, making the cast iron brittle, the morphology of the graphite in CGI does not allow cleavage neither crack propagations [2].

The characteristic morphology of CGI leads to strong adhesion between the graphite and the "steel" matrix, containing pearlite and ferrite phases. Stronger adhesion together with the rounded edges and irregular bumpy surfaces results in a reduction of the crack initiation and growth providing superior mechanical properties compared to gray cast iron which, traditionally, has been used in a majority of industrial cast components, e.g., engine blocks. Unlike more homogeneous and ductile materials (where usually quite long chips are formed), a specific feature of the CGI machining is the formation of segmented chips due to fracture, where the fracture zone is characterized by decohesion/separation of graphite flakes or nodules from the steel matrix structure. Cracks are developed primarily through the graphite grains due to the fact that the graphite grains act as notches in the much tougher matrix of the material [61].

The CGI has a 70% increase in tensile strength, 35% increase in Young modulus, and approximately twice the fatigue resistance of the conventional gray cast iron [25]. Table 2 shows some properties of gray cast iron, nodular, and CGI.

Hieber [60] found that the fracture of the CGI begins in vermicular graphite interface metal/matrix. Laempic and Henkel [79] attribute part of the increased wear on the cutting tool during the machining of CGI to the integration of graphite to metal matrix. According to Dawson [25], this characteristic assists in higher strength and higher toughness of the vermicular cast iron material. Andrade [2] found that CGI is 30 to 50% more wear resistant than gray cast iron. Guesser [50] states that in CGI, nodules of graphite will always be present, increasing the mechanical strength and toughness, however compromising casting, machinability, and thermal conductivity. The differences in the shape of the graphite, in combination with the matrix constituents, also affect the properties of cast irons such as hardness, ultimate tensile strength, thermal conductivity, damping, fatigue life, etc. The differences in these properties do affect the machinability of these grades of irons [67].

The CGI is used for making lighter engine blocks and heads. Having higher strength, the wall thickness of the whole complex workpiece are reduced ([86]); in other words, this material meets the requirements of higher pressures in the combustion chambers and consequently a more efficient engine with reduced weight/power ratio and lower rates of emission of harmful waste to the environment [2].

In cast iron, in general, the type of matrix, together with the form of the graphite, determine the main mechanical properties of the product [25]. Pearlite, for example, is a saturated form of ferrite, whose carbon in excess forms the cementite (Fe_3C) constituent, known as hard, with low machinability [18]. In one of his works, Xavier [139] examined the influence of cementite content in the pearlite of gray cast iron plates in

Table 2 Iron properties: gray, nodular, and CGI [123]

Property	Gray	Nodular	Compact graphite cast iron (CGI)
Ultimate tensile strength (MPa)	235	650	500
Hardness (HB)	200	270	225
Young modulus (GPa)	110	165	140
Fatigue resistance (MPa)	100	265	205
Thermal conductivity (W/mK)	48	28	35

drilling tests with high-speed steel (HSS) drills with 6 mm of diameter using three different cutting speeds. The researcher observed reduction on the tool lives by increasing the amount of cementite as presented in Fig. 2.

Dawson [25] showed in his work that the pearlite content in the matrix structure of CGI is directly proportional to the hardness and tensile strength of the material and consequently to its machinability too. According to him, an increase from 15 to 95% of pearlite causes a 60% increase in the tensile strength, whereas a 20% increase of the pearlite content caused an increase of 10 to 15% in the tensile strength.

Shao et al. [117] compared the influence of pearlite content between gray cast iron and CGI. They found that, for an equal content of pearlite, the CGI is around 10–15% harder than gray cast iron. They also concluded that engine blocks of CGI containing 70% of pearlite in their matrix have the same hardness of a block of gray cast iron with 100% of pearlite.

Phillips [103] studied the behavior of coated and uncoated cemented carbide tools in the turning and in the drilling of CGI with ferritic and pearlitic matrixes. In all tests, regardless the cutting material employed, the higher tool lives were obtained in the machining of the ferritic CGI.

The pearlite content in CGI, however, may depend on the type of the cutting process. Dawson [25], during turning and milling operations of CGI containing different proportions of pearlite in the matrix (50 to 95%), concluded that the pearlite content directly influenced the machinability of the cast iron. In general, the milling tool life increased when increasing the pearlite content. According to him, this result is because the pearlitizing elements propitiates good deformation and easy cleavage, as well as chip formation is in interrupted cuts. In the case of turning (continuous cut), the tool life decreased with increasing the pearlite content, showing that presumably pearlitizing elements of high alloys are very hard and abrasive for continuous cutting operations.

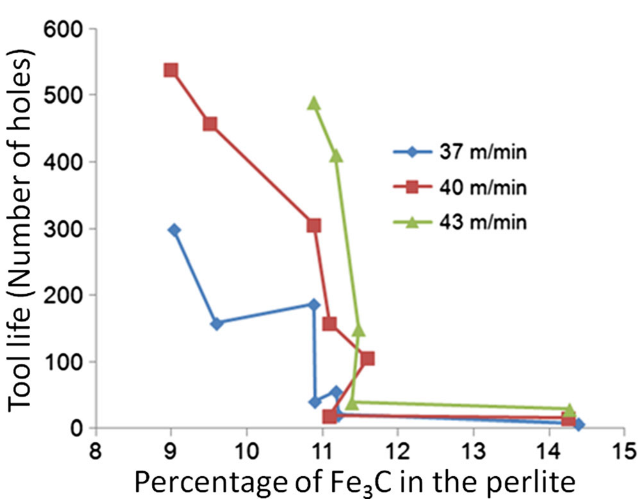


Fig. 2 Drill life behavior with increasing the Fe_3C content in the pearlite of gray cast iron. Adapted from Xavier [139]

In drilling tests of CGI with 70% of pearlite with twist drills of 8 mm of diameter, Dawson [24] found a 40% reduction in the tool life when compared to drilling of gray cast iron normaly used in engine blocks.

Table 3 shows the respective influences of the amount of pearlite in the properties of CGI with 10% of nodularity at 25 °C.

Cooling and demolding time can control the amount of cementite in the pearlite. In order to study the machinability variations of the CGI, Mocellin [90] carried out drilling tests in materials with different times of demolding: from 20 min to 2 h. For a longer demolding time, the machinability of the cast compacted graphite iron was better than that coming from the material with lower demolding time. According to him, this result was because the narrower Fe_3C lamellae (or fewer amount of cementite) in the pearlite in greater demolding time.

3 Machinability of cast iron

The production of cast iron has grown in recent years and represents much of the market for materials used in the industry [39, 51, 122]. According to Trent and Wright [137] and Nayyar et al. [94, 95], a large reason for the use of these materials in large engineering scale is not only concerning to the cost of the material and the casting process but also the economy of machining finished parts.

As previously discussed, adding alloy elements (silicon, magnesium, chromium, molybdenum, copper, among others) and applying appropriate heat treatment have greatly contributed to the improvement of the mechanical properties of these materials such as, for example, strength, hardness, stiffness, and toughness [17, 31, 91, 105].

Machinability is a term used to refer to the response of a material in machining, in terms of tool life, cutting force, quality of the machined surface, rate of material removed, or chip control. Improving the machinability of a material is of great interest because of the significant impact on industrial competitiveness. A method widely used to improve the machinability of a material, without altering the mechanical properties and microstructure, is by adding certain inclusions, the

Table 3 Physical and mechanical properties of CGI with 10% of nodularity at temperature of 25 °C containing 70 and 100% of pearlite [24]

Property	70% of pearlite	100% of pearlite
Ultimate tensile strength (MPa)	420	450
Hardness (HB)	190 and 225	207 and 255
Young modulus (GPa)	145	145
Yield strength (MPa)	315	370
Thermal conductivity (W/m °C)	37	36

so-called engineering inclusions, which favor the reduction of cutting forces, tool wear, and facilitate the chip rupture [37, 84, 137]. The addition of these elements directly influences the machinability of cast iron [20, 21, 73].

In addition to quantify how easy or difficult to machine a given material, the machinability is also used to quantify the performance of cutting tools and their geometries, especially in terms of their lives, and the performance cutting fluids during machining operations [84]. The machinability of a material is usually assessed by analyzing the tool life, machining forces, power consumption, chip form, and surface quality of the workpiece, depending on the application and project specifications [75].

In general, cast irons exhibit good machinability for almost all selected criteria, especially when compared to steel [128]. The variation of the machinability within the grades of cast iron depends on their chemical composition and microstructure [15]. The main effects are reduction of carbon content in the matrix (due to the appearance of free carbon that weakens the matrix and, consequently, tends to improve the machinability), increase in silicon content (decreasing the size of built up edge (BUE), thereby improving the machinability of the material, particularly when the BUE is an important criterion), and the increase in the pearlite content (increasing hardness and hence decreasing the machinability of the material) [121]. Sahm et al. [109] state that the chemical composition is not the only influential parameter in the machinability of the cast irons because the form of graphite also exerts a strong influence. According to Mamedov et al. [85], graphite as a component of relatively low hardness as compared with the other constituents of the matrix, produces discontinuities in the material, thereby enhancing the chip breakability during the machining process. For Marwanga et al. [87], graphite acts as a lubricant, reducing friction between the workpiece and the tool and reduces the risk of micro weldings; thus, the overall effect is to improve the tool life.

Within a grade of cast iron, gray and nodular, those presenting lower hardness and tensile strength are seen as materials that exhibit the best machinability [7]. When compared, only these two materials, nodular cast irons, have lower machinability than gray cast iron, because the latter has flake-shaped graphite that act as stress concentrators in the shear plane, thus facilitating cutting. The sphered-shaped graphites are less effective in "weakening" the material in the shear plane and flow zone and may in some cases behave as highly ductile materials [143]. According to Anon [3] and Sandvik [110], the presence of nickel and copper in nodular cast iron improves the machinability. These elements act to reduce the cutting force and the surface roughness of the workpiece.

Opländer [97] states that during the machining of gray cast iron, the graphite flakes slide over loads, appearing that they are "soft." The author also says that the same does not occur with nodular and vermicular graphites. This is because the nodules come off and will never be seizured by the tool during the machining process. They are only deformed and displaced. On the other hand, the graphite from CGI does not detach and slip because they are strongly "anchored" in the matrix. The author has also concluded that the type of chip obtained depends not only on the form but also on the size of the graphite and its interaction with the matrix structure.

Compared to gray cast iron, the difficulty in machining the CGI is associated with two factors: high mechanical strength (involves large cutting forces) and the absence of manganese sulfides in its microstructure (always present in gray cast iron and during machining are deposited on the cutting tool surfaces, thus ensuring a local action of solid lubricant) [102, 104].

In turning process with pCBN inserts, Dawson [27] found a reduction in the machinability of CGI by increasing the amount of vermicular graphites (Fig. 3). He also showed a reduction in the machinability with increasing nodular graphite content compared with material consisting essentially of lamellar graphite. Mocellin [90] also proved that the machinability of gray cast iron is better than that of CGI with mechanical strength of 450 N/mm^2.

Heck et al. [58] studied the influences of various metallurgical variables on the machinability of cast iron, focusing his research on the form of graphite, effects of alloying elements and the amount of pearlite. They concluded that the machining of CGI is much more difficult than that of gray cast iron, especially at high cutting speeds, making this the only reason why this material is not used to a greater extent in volume production scale. According to Reuter et al. [104], the difference in machinability between these materials is explained by the formation of MnS layer on the surface of the tool when machining gray cast iron. This layer is not formed in CGI, since the sulfur content in the material is about 10 times lower than in gray cast iron. Thus, the sulfur content plays a very important role during machining, as shown in Fig. 4. The MnS layer acts as a solid lubricant and prevents adhesion of the work material on the tool rake face. According to Dawson [25], the sulfur, together with the shape of the graphite, is

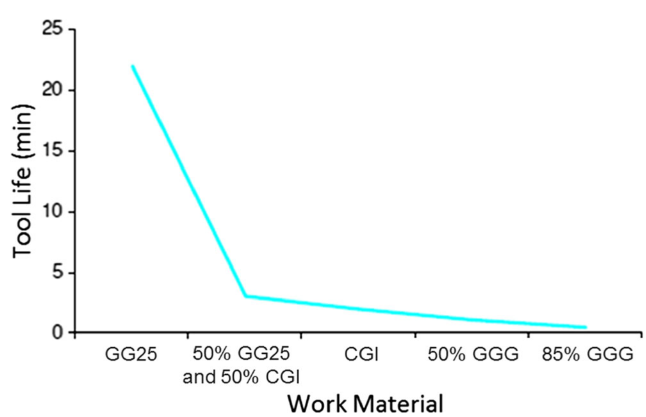


Fig. 3 Influence of the graphite form on the tool life in turning of cast iron with PCBN tools (v_c = 800 m/min) [27]

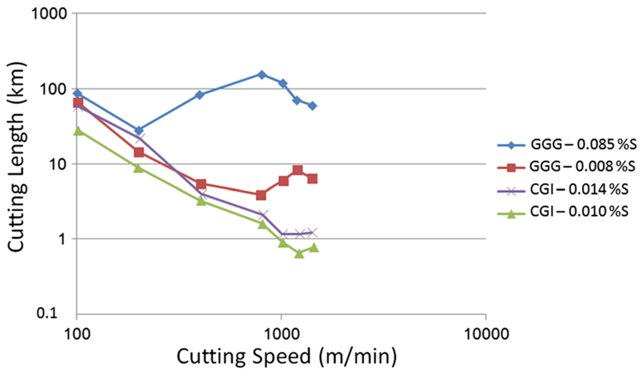


Fig. 4 Effect of sulfur content in the machinability of different cast irons. Adapted from Reuter et al. [104]

considered the most significant difference of CGI as compared to gray cast iron. The content of this element in gray cast iron is between 0.008 and 0.09%. In the CGI, the sulfur content is in the range of 0.005 to 0.025%, because the compacted graphites are stable only at low levels of oxygen and sulfur. The sulfur present in the cast iron reacts with manganese (Mn), forming molybdenum disulfide inclusions (MnS_2), which lubricate the tool, forming a protective layer at the chip-tool interface and serving as barrier against the wear mechanisms such as abrasion and diffusion. The CGI, however, does not show the formation of such a layer, because besides having only a tenth of the sulfur that gray irons have, the magnesium (Mg) is added as a necessary element for the formation of the compact graphite. The Mg has more chemical affinity with sulfur than manganese, which thus favors the formation of magnesium sulfide instead of the formation of manganese sulfide, and consequently, there is no formation of the protective layer [105].

On the other hand, ductile irons (DI) has the graphites in the form of nodules (spheres), thereby with higher strength than both flaked and compact graphite irons. Consequently, the machinability of ductile irons are in general lower than its competitors. Continuous casting of ductile iron uses huge graphite matrixes that generally produces bars with very large cross sections. This in turn promotes variation in the mechanical properties along this cross section that affects the machinability. In order to study this effect, De Sousa [28] has carried out tool life tests in turning with cemented carbide tools (K35 grade, coated with TiN) of bars of ductile iron (DI) with 203 mm of diameter and divided the cross section in three regions (core, intermediate zone, and periphery) according to Fig. 5a to study the variability of the machinability. The three regions were characterized previously. The core showed a ferrite/pearlite matrix and average hardness of 181 HB, the intermediate zone a ferrite/pearlite matrix and average hardness of 180 HB, and the periphery a ferrite matrix and average hardness of 167 HB. Table 4 presents details of the microstructures of the three regions. The machinability results are shown in Fig. 5b. The ferrite matrix and the lower hardness of the periphery prevail and showed smaller flank wear with the same amount of material removed.

3.1 Forces and stresses in the machining of cast irons

The machining of cast iron can vary from very easy, as in the case of ferritic cast iron, until very difficult, as in the case of white cast iron [43, 44]. The chip-tool contact length during the machining of cast iron is small (even when subjected to high-speed machining), which favors the achievement of high stress values at the tip of the tool. The small chip-tool contact length obtained during machining of this material also promotes relatively low machining forces, in addition to low power consumption [121]. According to Trent and Wright [137], graphite flakes can be large and occupy a considerable area on the extension of shear planes, also contributing to reduce the machining forces. A flake may significantly extend through all the shear plane.

Table 5 shows the cutting (F_c) and feed (F_f) forces in the machining of gray cast iron with graphite flakes and pearlitic matrix compared with a medium carbon steel. Note that the feed forces of the cast iron are greater than the cutting forces

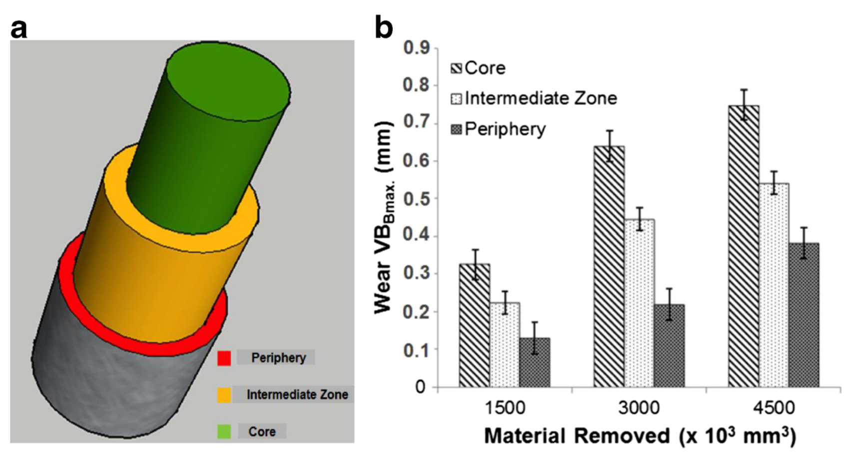


Fig. 5 **a** Cylindrical bar divided in three regions. **b** Tool life test results [28]

Table 4 Average results of the microstructure of the three regions of the cylindrical bars of the DI [28]

Region	Pearlite matrix (%)	Carbides (%)	Nodularization (%)	Graphite particles/mm^2	Graphite size (μm)
Core	21.3	0	96.8	102.3	38.1
Intermediate zone	17.5	0	98.4	152.6	32.4
Periphery	4.4	1	97.8	670.6	15.8

(during machining of steels, the opposite occurs and the cutting forces are generally greater than the feed forces) and around the same levels of the feed forces for steels. According to Trent and Wright [137], feed forces higher than cutting forces are common in the machining of gray cast iron and the best explanation for this is the smaller amount of plastic deformation in the primary shear plane than in the secondary shear plane. Sousa et al. [126] also found similar behavior of the force components during the machining of some metallic materials, including gray cast irons.

Excessive tool flank wear, due to the presence of hard particles and adhesion of the workpiece material in the cutting tool surfaces during the machining of cast iron, may increase the machining forces [1]. Grzesik and Malecka [48] studied the behavior of the machining forces of nodular cast iron EM/GJS-500 (3.78% C, 2.46% Si, 0.32% Mn) with ferritic/pearlite microstructure (50% pearlite, 40% ferrite, and 10% graphite), ultimate tensile strength of 500 MPa, and hardness of 175 HB. They presented the evolution of the machining forces with tool wear for two types of ceramic tools (Si_3N_4 and Si_3N_4 coated by Al_2O_3/TiN) (Fig. 6). Note that there is an excessive increase in the machining force of the uncoated tools. According to them, this is because uncoated tools have higher levels of flank wear than the coated tools. According to Schneider and Richter [115] and Lau et al. [80], when the wear rates are high, it tends to promote high machining forces.

Sousa et al. [126] studied the behavior of the machining forces in turning of EM-245 gray cast iron (hardness = 205 HB, ultimate tensile strength = 245 MPa; fatigue strength = 100 MPa) with silicon nitride (Si_3N_4) ceramic tool. In this work, they found that the interval of the cutting parameters for built up edge (BUE) taking place is much higher than when machining steels. According to Trent and Wright [137], the formation of discontinuous chips and the huge differences of properties of the second phase and the matrix of the cast irons contribute to this higher range.

Table 5 Comparison of the machining forces of gray cast iron and medium carbon steel (f = 0.16 mm/rev; a_p = 1.25 mm) [137]

Cutting speed, vc (m/min)	Pearlitic gray cast iron		Medium carbon steel	
	F_c (N)	F_f (N)	F_c (N)	F_f (N)
30	222	232	520	356
61	245	285	490	364
91	245	320	445	325
122	267	338	422	313

The discontinuous type of chip produced in gray cast iron results in a process with low power consumption, low temperature on the tool rake face, and short time of contact between the chip and the tool during machining. Thus, according to Silva [120], extensive chemical reactions at the tool-chip interface are avoided.

Camusçu [14] studied the behavior of the cutting force with increasing cutting speed (shear rate), during turning of nodular cast iron (3.62% C, 2.57% Si, 0.08% Cr, 0.16% Mn) with hardness of 246 HB, using ceramic tools (Fig. 7).

He found that, regardless of the cutting tool, increasing the cutting speed resulted in a reduction of the machining forces. According to Ko and Kim [74] and Toh [133], the reduction of the machining forces when increasing the cutting speed (shear rate) is related to the increasing of temperatures in the shear zones. Hence, resulting thereby in the reduction of the shear strength of the work material and in chip thickness formed during the cutting, while at the same time, the chip-tool contact length is diminished. Dumitrescu et al. (2005) and Saoubi et al. [114] found in their research similar results stresses even more the reduction of the machining forces against increasing cutting speed.

Ljustina et al. [82] studied the effect of graphite nodularity on the machinability of cast irons in orthogonal cutting. A microstructure-based model of the cast iron material has been developed based on the analyses of micrograph images. The image analysis combines pearlitic grains with graphite nodules to produce the microstructures. Continuous deformation behavior of pearlite and graphite phases is described using the Johnson–Cook (JC) viscoplasticity model, including temperature dependence. In Fig. 8, a typical distribution of the effective plastic strain during machining is shown. For illustration purposes, the graphite grains are removed (white areas) to illustrate the connection between development of plastic strain and morphology. It appears that the shape of the graphite grains changes during the machining process, where nodules become elongated in the direction of chip flow. Effective plastic strain develops first through the shortest distances between graphite grains, which means that cast iron deforms easier along the grain boundaries. Cracks tend to develop along preferred patterns through graphite grains if the crack promoting “notches” (defined by the graphite morphology) are not too blunt. In

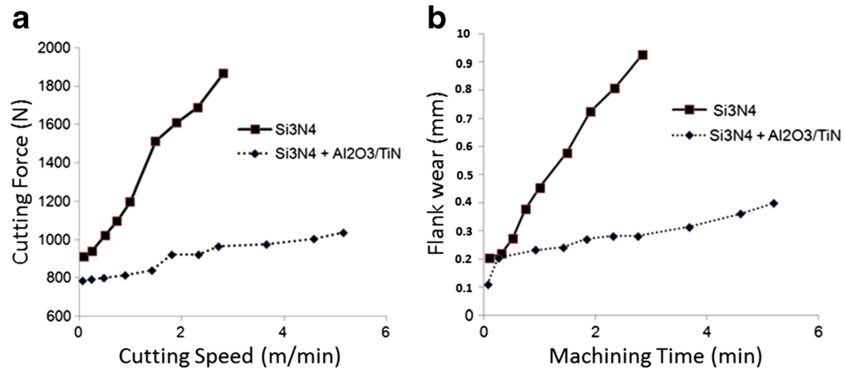


Fig. 6 Performance of Si_3N_4 and Si_3N_4 coated with Al_2O_3/TiN ceramic tools in the machining of nodular cast iron EM/GJS-500. **a** Cutting force. **b** Flank wear [48]

reality, this squeezing out of graphite on the surface influences the frictional conditions during the machining of cast iron.

Figure 9 shows the von Mises stress distribution pattern during machining. Significantly higher magnitudes of the effective stress are obtained in the pearlite as compared to the graphite phases. This is due to the significantly higher yield stress and higher stiffness in the pearlite as compared to the graphite. Note that fairly high shear strain is required to mobilize the stress response in the highest deformed areas of Fig. 9.

3.2 Power consumption in the machining of cast irons

The specific cutting energy (cutting force divided by the cutting area) tends to increase with increasing hardness and strength of the machined material [89] and tends to decrease with increase in the feed rate and cutting speed. This is because increasing the feed rate, the cutting area increases and increasing the cutting speed, the cutting force decreases. However, the cutting power is practically composed only of the product of the cutting force and the cutting speed, and thus, the power consumption will increase with increasing of both feed rate and cutting speed [84].

The machining performance of a material depends on the stresses in the shear planes, which, in turn, depend on the mechanical strength and the presence of alloying elements. The machining performance also depends on the cutting conditions [31]. The power consumption generally increases with increasing cutting speed, although the cutting forces are reduced, since this promotes adequate softening of the material and can prevent adhesion in the cutting area. The rake angle has also a great effect on the cutting power, which decreases with increasing rake angle. Application of a good lubricant will also reduce forces and consequently the power consumption [23]. The power will increase with increasing cutting time (or cutting length) since the tool wear will progressively increase [84].

However, some of these behaviors are more clear when machining relatively soft materials and not very effective in the machining of cast irons because of the discontinuous type of chip formed [84]. Compared to steels, the power consumption when machining cast irons are lower because of the shorter chip-tool contact length of the discontinuous chips.

Barbosa et al. [5], with the goal of searching for materials with improved properties, have conducted drilling tests to check the machinability of two austempered ductile iron − ADI (ISO 800-10 and ISO 1.050-6) and a pearlite

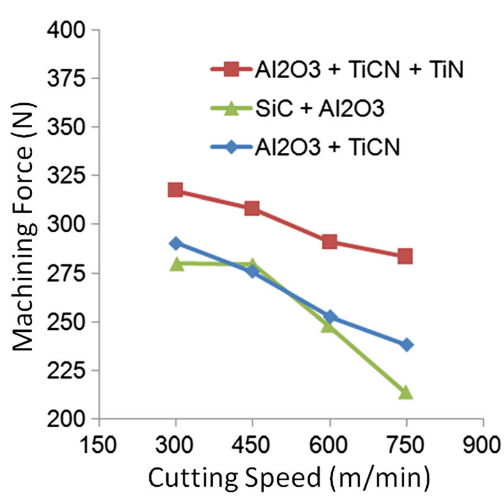


Fig. 7 Machining force against cutting speed when machining the nodular cast iron with several ceramic tools [14]

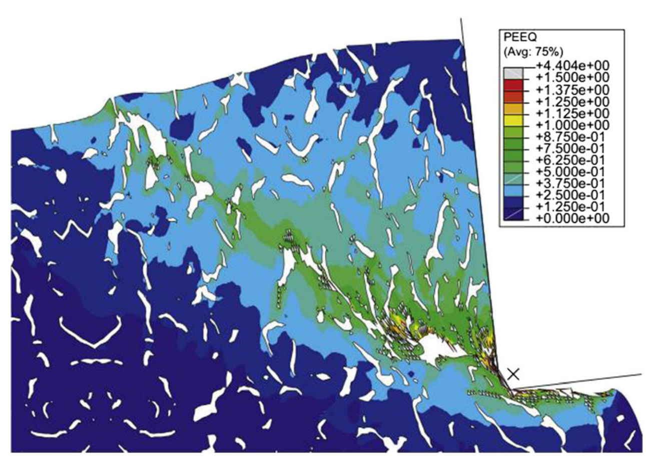


Fig. 8 A typical distribution of the effective plastic strain during the machining simulations. The cutting speed is 350 m/min and the nodularity is 0% [82]

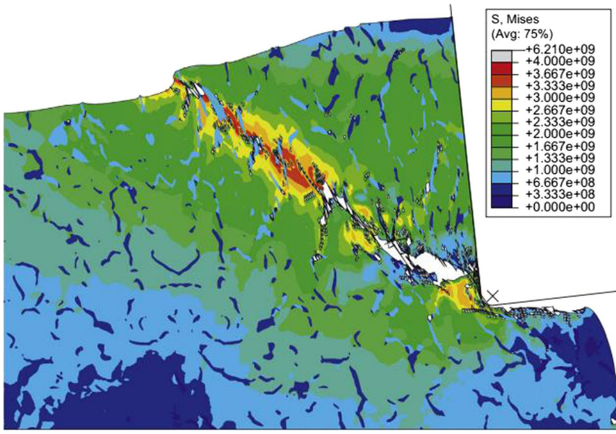


Fig. 9 A typical distribution of the von Mises effective stress during the machining simulations. The cutting speed is 350 m/min and the nodularity is 0%. The stresses of the legend are in Pa [82]

ductile iron (FE 70003), for comparisons. They have used K20 cemented carbide twist drills coated with multilayers of TiN/TiAlN applying flood and MQF (minimum quantity of fluid) techniques and consider the thrust force, torque, and power consumption as the output parameters. Figure 10 shows the results of the power consumption found.

They concluded that the results are closed related to the work material microstructure and hardness and that austempered iron can be an interesting alternative for substituting ductile irons.

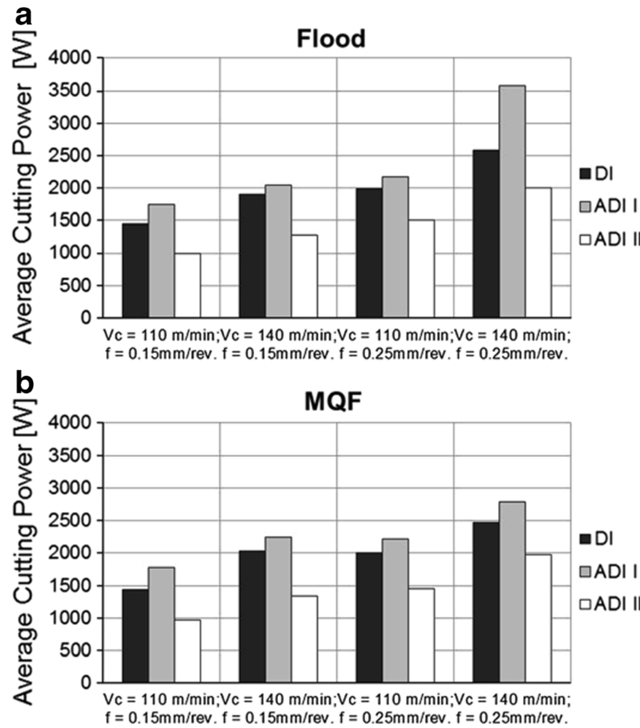


Fig. 10 Power consumption in drilling austempered ductile irons − ADI I (ausferrite − 288 HB), ADI II (ausferrite + ferrite and residual spheroidized pearlite − 203 HB) and pearlite ductile iron − DI (pearlite + 2% of ferrite – 269 HB) [5]

3.3 Temperature in the machining cast irons

The temperature distribution on cutting tools during the machining of cast iron differ from those observed when machining steels [137]. Since the chips are not continuous, the maximum temperature is observed very close to the cutting edge; thus, the maximum cutting speed is limited by plastic deformation of compressive nature [70]. The excessive increase in temperature can lead to microstructural changes, residual stresses in the subsurface layers, tolerances errors and distortions, in addition to increasing tool wear, and adhesiveness of work material on the tool's cutting edges [72].

Souza et al. [128] examined the behavior of the average cutting temperature at different feed rates and a constant cutting speed of 300 m/min when machining the gray cast iron EM-245 (hardness = 205 HB, ultimate tensile strength = 245 MPa, the fatigue strength = 100 MPa) (Fig. 9a). They observed that increasing the feed rates the temperature decreases. According to Bates [6] and Fang [38], the increase in the feed rate results in increasing of the areas of the primary and secondary shear planes, giving room to greater heat dissipation in the tool and workpiece. However, if the increase in the feed rate is not effectively increasing the chip/tool contact area, which generates greater heat dissipation between the chip and the tool, the cutting temperature will not reduce and rather increase. Figure 9b shows the influence of the cutting speed on the cutting temperature. In this case, the increase in cutting speed resulted in increased temperature. The heat generated during cutting must be dissipated by the workpiece, the chip, and the environment. According to Souza et al. [128], in the case of gray cast iron, which is a good heat conductor but produces discontinuous chips, the heat generated in the primary shear zone is smaller than those generated in the secondary shear zone. Hence, a large quantity of heat developed in the cutting zone has to be dissipated by the tool and the chip. The machining temperature is strongly influenced by the cutting speed, which will exert a great influence on the tool performance, especially at high speeds [16, 35, 59, 101, 132]. In general, an increase in the cutting speed increases the cutting temperature due to its influence on the strain rates in the primary and secondary shear planes [62, 72, 118].

Ljustina et al. [82] showed their results of the temperature distribution when machining the CGI cast iron at cutting speed of 350 m/min, using numerical simulation by finite element method (Fig. 11). Extremely high temperature, 1300 °C, can be observed at the chip-tool interface, indicating the poor machinability of this material when the temperature is used to assess it.

When machining steels, the tool geometry changes, such as large rake (γ_r) and clearance angles (α_o) up to a certain range (e.g., between 10° to 25° for the rake angle and 4° to 7° for the clearance angle), tool materials with low friction coefficient

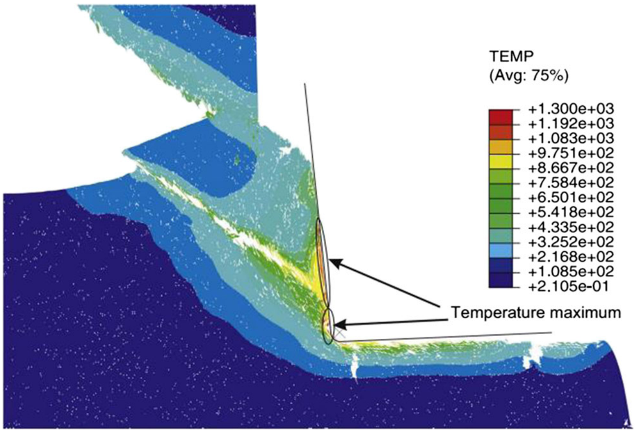


Fig. 11 A typical temperature distribution during the orthogonal machining simulations. The cutting speed is 350 m/min [82]

and the presence of chemical elements in the work material which enhance the chip flow, inhibit the excessive rise of the temperature, because in these conditions, the chips flowing over the rake face is facilitated and lesser heat is generated [83, 137, 140]. However, when machining gray cast iron, the tool geometry does not have much effect in reducing the heat generated, because of the short chip/tool contact area, characteristic of discontinuous chips. In this case, heat dissipation is more important and negative rake angles provide greater and stronger tool wedge, with higher heat dissipation capacity [84].

Tool wear also have a great influence on the cutting temperature. Increasing in flank wear increases the cutting temperature because they increase the shear forces in the shear planes and promote the formation of a third and important heat source between the surface of the workpiece and the tool, also named as tertiary shear zone [84, 98].

3.4 Surface integrity when machining cast irons

The surface integrity plays an important role in the manufacture of machine components (Fig. 12). In machining processes, the surface integrity (roughness, microhardness on the machined surface and beneath, residual stresses, surface and subsurface cracks, etc.), and the dimensional accuracy are influenced by the machining process, cutting conditions, tool geometry, tool material, type of chips, tool wear, and rigidity of the machine tool (vibration) [10, 69]. The surface integrity of a machined component, in general, is a result of a process that involves plastic deformation, elastic recovery, heat generation, dynamic recrystallization, vibration, residual stresses, and even chemical reactions and can promote changes in surface finish (surface roughness and burrs) and subsurface (plastic deformations, residual stress, and microhardness) [68, 84, 113, 130]. The high product quality is only achieved with the use of suitable machining parameters and when monitoring the machining process [43, 44].

In general, the higher the hardness of the work material, the lower is its surface roughness. In the case of cast irons, the surface roughness is directly influenced by certain material characteristics, such as hardness and microstructure, for instance [1].

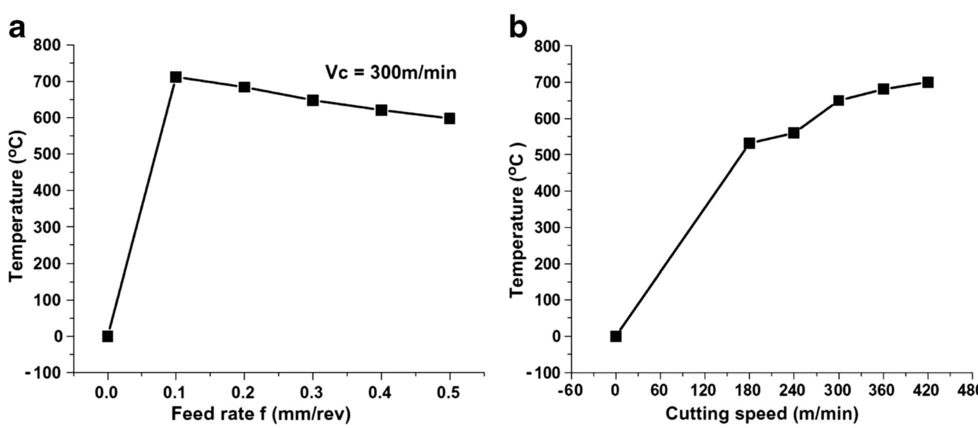
Low tool wear rates and high rates of material removal, plus the low value of the cutting forces and power consumption are characteristics of machining of cast irons [128]. During the machining of this material, graphite particles determine the level of surface roughness, while the matrix determines the tool life extension [14].

The built up edge (BUE) is formed when cutting under low cutting speeds and can occur at higher speeds than when cutting steels. Even in interrupted cutting, the presence of the BUE is more stable because of the formation of discontinuous chips [137]. According to Trent and Wright [137] and Machado et al. [84], the presence of the BUE directly influences the level of finish of the machined surface.

In the machining of cast iron, the produced surface is matte, which makes this material ideal for sliding contact [130, 137]. The addition of nickel and copper to the cast irons improves machinability by reducing cutting forces and surface roughness of machined parts [116].

Camusçu [14], using different cutting tools, observed the behavior of surface roughness along the cutting speed during machining of nodular cast iron (3.62% C, 2.57% Si, 0.08%

Fig. 12 Average temperature behavior during the machining of gray cast iron EM-245 against: (**a**) feed rate, and (**b**) cutting speed [128]



Cr; 0 16% Mn) with a hardness of 246 HB (Fig. 13). He found that, unlike the wear behavior, the surface roughness did not increase continuously with the cutting length. The researcher noted the continued increase in surface roughness along the cutting length in just a few particular situations, and generally, the behavior of this parameter was quite random. According to him, this characteristic is directly related to progression of flank wear, since for most cases, the curve of the surface roughness showed the "zig zag" pattern, i.e., the surface quality has deteriorated to a determined cutting length value, improving to some middle range, and subsequently began to deteriorate again. Therefore, it is difficult to draw general conclusions about the influence of wear on the surface roughness when machining cast irons. This behavior were also seen in the works of Ghani et al. [43, 44], Saoubi et al. [114], Tonshoff et al. [135], Dumitrescu et al. [34], and Koshy et al. [77].

Many other factors, beside the tool wear, can have an effect on the quality of the machined surface, such as the heterogeneity of the work material and the random distribution of the graphite nodules, both characteristics found mainly in nodular cast iron [78, 116, 133, 143].

Some undesirable effects such as excessive increase in the ductility of the work material and the presence of the BUE directly affect the surface finish of the cast irons, i.e., causing high surface roughness and large burrs [12]. According to Fengzhang et al. [40], the best way to minimize the surface roughness during machining is through proper selection of cutting tools and cutting conditions. Machado et al. [84] and Trent and Wright [137] suggested the use of low feed rates; cemented carbide ('K' grade) cutting tools, either coated or uncoated; negative rake angle; and large nose radius tool in order to reduce the surface roughness when machining cast irons. The use of ceramic or pCBN tools allows machining at high cutting speeds, thereby generating a good surface finish and may, in some cases, eliminate grinding operation ([141]); however, it should have a strict control over the tool wear level.

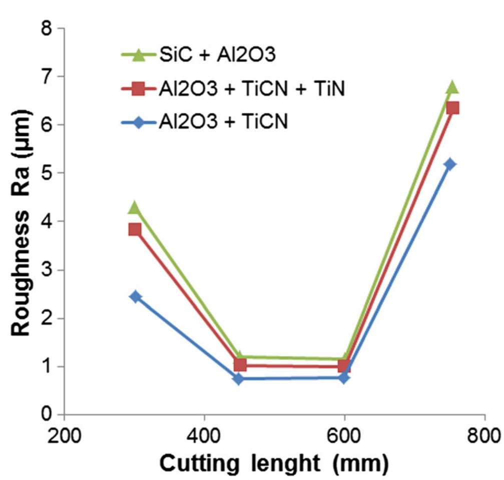


Fig. 13 Behavior of R_a roughness along the cutting length during machining of nodular cast iron (HB 246) with ceramic tools. Adapted from [14]

3.5 Cutting tools for machining of cast irons

The tools commonly used for the machining of cast irons are high-speed steel, cemented carbide—grade "K" (coated by TiN, TiAl, TiAlN multilayers or uncoated), ceramics (Si_3N_4; Si_3N_4 + Al_2O_3—SIALON; Al_2O_3 + SiC—Whisker; Al_2O_3 + TiC—Mixed), ultrahard (pCBN-H or pCBN-L, where H is the mean high percentage of CBN content and L low CBN content) [84, 113, 137]. The tools for the machining of cast iron must be abrasion resistant and have high toughness, besides being chemically inert in order to prevent interactions with the work material [143]. The use of high hardness coatings on cutting tools has enabled the milling at high speeds. The TiAlN coating applied on the cemented carbide tools of the "K" grade has extensively been used in the machining of cast iron in order to improve productivity and reduce costs [57].

The high-alloyed and the low graphite carrying a large amount of carbides cast irons, for examples, have poor machinability. In such cases it is common the use of the 'K' grade of carbide coated with TiAlN, ceramics or pCBN tools [56]. According to Smith et al. [124], TiAlN coating is able to maintain high hardness and oxidation resistance even at high temperatures. Yigit et al. [143] found in their work, using TiAlN coatings with several thickness, that 10.5 µm is the most appropriate coating thickness when machining nodular cast iron.

The Al_2O_3 and Si_3N_4-based ceramic tools have low chemical affinity with cast iron, which greatly improves the surface finish, even at high cutting speeds [137]. Table 6 presents some cutting conditions recommended for machining cast irons with HSS, carbide, and ceramic base of Al_2O_3 and Si_3N_4 tools.

Since the publication of Trent and Wright [137], obviously, the cutting tool materials and their coatings have had great improvements, and then, the cutting parameters increased, and nowadays, for coated cemented carbide, the recommended cutting speeds can range from 500 to 800 m/min, depending on the coating properties, resistance of the gray cast iron, tool geometry, and other cutting parameters (feed rate and depth of cut). Using pCBN for instance, the magnitude of cutting speed can reach the average value of 1700 m/min [111].

Dealing specifically with nodular cast iron, which for the most part, has a high ductility microstructure, the most suitable machining tools are ceramic, particularly the SiAlON and pCBN (polycrystalline compact boron nitride) [80]. Ceramic tools (aluminum oxides, silicon nitrides, mixed ceramics, etc.) allow cutting speeds in the range of 350 to 800 m/min [65, 113]; however, the chip-tool contact length is significantly increased compared to the pCBN tools [30]. The use of these tools implies in greater productivity, and better surface

Table 6 Cutting speed recommended for gray cast iron with different cutting tools [137]

Brinnel hardness	HSS tools (f = 0.5 mm/rev) (m/min)	Cemented Carbide tools (f = 0.5 mm/rev) (m/min)	Ceramics tools (Al_2O_3 ou Si_3N_4) (f = 0.5 mm/rev) (m/min)
115–200	40	120	1500
150–200	25	90	1300
200–250	20	70	900
250–300	12	55	600

finishes in manufactured parts when machined at high cutting speeds and low feed rates [29, 143].

The silicon nitride-based ceramic has high mechanical strengths due to the covalent bonds, along with its chemical properties that are hardly affected at elevated temperatures [119]. According to Kato et al. [69] and Machado et al. [84], these tools also have high resistance to thermal shock and abrasive and adhesive wear (predominant wear type on cutting tools when machining nodular cast iron) when compared to aluminum oxide-based ceramic. Ghani et al. [43, 44] monitored the wear and the machine vibration in their experiments and observed that alumina-based ceramic tools are not satisfactory for machining nodular cast iron, because of their low toughness.

On the other hand, white cast iron is very difficult to machine. When using the “K” grade of cemented carbide, the cutting speed is somewhat in between 3 and 10 m/min, and when the tool is a ceramic or a pCBN, the cutting speed can be increased to 50 m/min [137].

According to Santos and Sales [113], the evolution of pCBN tools with low CBN content (named pCBN-L, with around 50% of CBN grains and the rest composed by a ceramic binder) and high CBN content (named pCBN-W, with around 90% of CBN grains and the rest composed by a metal binder, cobalt) give important options for applications in hard turning, and this includes turning of white cast irons at cutting speeds beyond of 200 m/min, or higher.

For machining of gray cast iron in continuous cutting (turning and boring, for instance) at high speeds, pCBN tools can be applied; however, they cannot be employed in the machining of compacted graphite iron, because of the drastic reduction in the cutting length [88]. For the gray cast iron, the use of pCBN cutting tools allows a significant increase in the cutting speed and consequently, a much higher productivity is obtained when compared with the conventional cemented carbides [105]. The cutting speeds commonly employed for pCBN tools when machining gray cast iron should be in the range of 500 to 1500 m/min ([41]); however, cutting speed over 2000 m/min are possible in some specific cases [47].

In machining with coated tools, fragmentation of the coatings can occur and one of the reasons is the poor adhesion of the coating to the substrate. This will accelerate tool wear and shorten tool lives. In order to improve the adhesiveness of the coating to the substrate, Viana et al. [138] have produced laser modifications (parallel ridges—micro textures) on the substrate of cemented carbide tools before coating (TiAlN and AlCrN) and tested them in face milling of compact graphite iron (CGI—grade 450). Commercial coated tools (microblasted before coating—the normal procedure use in their production) were also tested as a base of comparison. The laser-textured outperformed the commercial microblasted tools in terms of tool life. Scratch tests with progressive loads and Rockwell indentation proved the better adhesiveness of the laser-textured tools as compared to the microblasted. This reduced fragmentation/delamination of the coatings and diminished the abrasive wear during the milling tests.

3.6 Tool wear in machining of cast irons

The type of wear that prevails in a specific machining process depends on the pair of the tool and workpiece materials involved, as well as to the cutting conditions and dynamic stability of the machine tool [72]. Specifically, in the machining of cast iron, flank wear tends to prevail normally developed by adhesives and abrasive wear mechanisms [137]. The abrasion is due to the presence of hard particles in the cutting area, which may come from the matrix that contains hard precipitates, such as SiC, Fe_3C, WC, TiC, among others, depending on the chemical composition of the work material, or when hard particles are plowed out from the tool by attrition. Gastel et al. [42] evaluated the use of polycrystalline diamond (PCD) tools in the machining of cast irons and the results showed that due to the high chemical affinity of the PCD with any kind of cast iron, the use of them are not recommended in these materials, due to very low tool lives promoted by adhesion wear. Moreover, this wear mechanism is thermally activated, and at around 750 °C, allotropic form of the carbon on the PCD tools changes from body center cubic (diamond) to hexagonal compact (graphite), particularly when this temperature remains for more than 1.5 min and the tool drastically loses its mechanical properties, leading the tool to a catastrophic failure [84, 113, 137]. PCD can be applied for machining this kind of materials if the friction coefficient is drastically reduced in a way that the heat generation and the temperature become at low levels, eliminating the diffusion wear mechanism. This is possible with the use of cutting fluids and in cryogenic machining using CO_2 (temperature from −80 to −85 °C) or LN_2 (temperature around −195.8 °C). Cryogenic machining, however, needs further careful investigation before it proves as being effective technically and economically and feasible.

Cast irons are ordinarily machined without the use of cutting fluids. The lubricant action provided by the graphite permits the success of dry machining. However, when machining the CGI, due to extremely high heat generation, a cutting fluid with good coolant ability is frequently recommended [84, 113, 129]. The work developed by Nayyar et al. [94, 95] also showed the need of the application of an efficient cutting fluid in a continuous machining operation of CGI and SGI (spheroidal graphite iron). The tool wear mechanisms in boring operation of different grades of these materials were also studied for dry and wet conditions. Both CGI and SGI have shown adhesion as the prevailing wear mechanism under dry conditions as compared to abrasive wear in wet conditions, using a cutting speed of 300 m/min. These results help to design suitable inserts for CGI and SGI machining and highlight the importance of using cutting fluids when machining CGI and SGI in continuous cutting operations.

In the case of white cast iron, the common practice is also dry machining, but in this case, due to the very high resistance of the material that does not allow cooling, demanding reduction of the shear strength during the process of chip formation by the high temperatures. In such cases, application of a coolant maintains the level of shear resistance of the material in the cutting zone so high that the tool most often fails catastrophically.

Wear of chemical origin accelerated by high temperatures in the machining of CGI at high cutting speeds was observed by Kalhofer [66] using cemented carbide tools coated with Al_2O_3, AlON, and TiB_2. In this application, erosion of the coating occurs, due to the material transfer between the chip and the tool.

Ghani et al. [45] experimentally investigated the role of green (or dry) machining on tool life and surface finish, in turning of the ductile cast iron FCD700. They compared dry and wet conditions, using commercial oil- and palm oil-based MWFs, at the same machining parameter set-up. The results show that dry machining performance is comparable to that of wet machining. It was found that the performance of wet machining, in terms of tool life, was better than dry machining; however, the surface quality of dry machining was almost similar to that of wet machining. It was evident from their results that green machining can be conducted at high cutting speeds, low feed rates, and depths of cut, and using suitable coated tools.

In drilling, adhesion and accumulation of material in the flutes of the drill increase the torque and temperature, frequently causing catastrophic failure of the tool [106].

Bonifacio and Diniz [9] developed a study on turning of gray cast iron with ceramic tools at different cutting speeds. Figure 14 shows the results of the tool life tests, considering the average flank wear VB_B on mixed ceramic tools Si_3N_4 + Al_2O_3/TiN using three different cutting speeds of 100, 160, and 240 m/min. The best results were found when using a cutting speed of 160 m/min. The use of the lowest cutting speed promoted chipping and the highest accelerated tool wear.

Camusçu [14] performed similar tests, but during the machining of nodular cast iron (HB 256) using different ceramic tools at different cutting speeds (Fig. 15). The alumina ceramic tool coated with TiN showed the best performance. According to the author, this result confirms that the high hardness of the TiN coating (3000 kgf/mm^2, [100]) strongly improved the resistance of the ceramic tools during machining of nodular cast iron.

In milling of gray cast iron JIS/FC300 (ultimate tensile strength of 300 N/mm^2), Kato et al. [69] observed the wear behavior of pCBN tools. They concluded that even at high cutting speeds, the tool wear is greatly reduced, and this parameter did not affect much the results. This behavior is normally observed in chamfered tools, which needs a minimal cutting speed to better shear the work material and consequently show appropriate results. This minimal cutting speed strongly depends on the chamfer design as well as on the properties of the workpiece material. The cutting speeds used by Kato et al. [69] are higher than the minimal, when the tool wears quickly due to attrition being the dominant wear mechanisms with high wear rate and reduced the tool life.

Pereira [101] observed, in the machining of gray cast iron with β-Si_3N_4-based ceramic tool, that the increase in the cutting speed resulted in reduced tool wear. Such atypical behavior is of great importance in the highly competitive industries such as automotive, reducing production costs and increasing productivity. According to the author, this behavior is a result of a reduction in the machining force components due to the

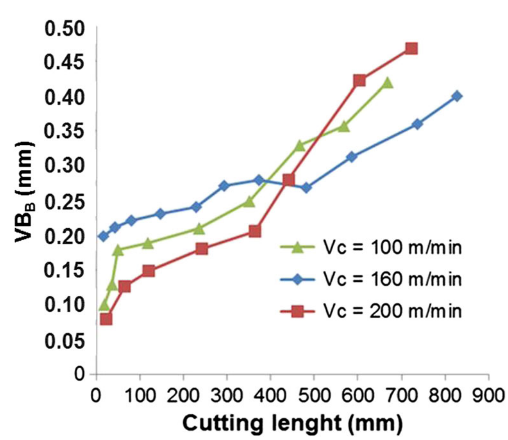


Fig. 14 Tool lives of Si_3N_4 + Al_2O_3/TiN ceramics in turning of gray cast iron. Adapted from Bonifacio and Diniz [9]

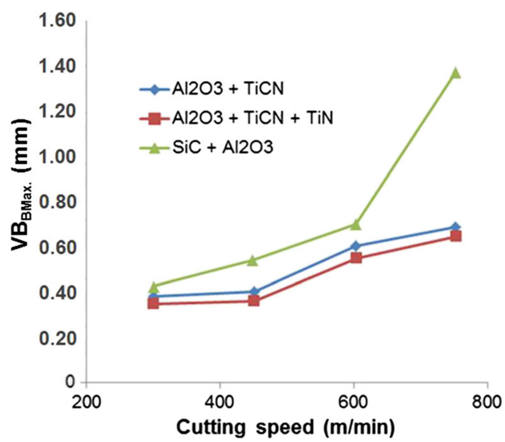


Fig. 15 Tool flank wear versus cutting speed when turning nodular cast iron (246 HB) with ceramic tools. Adapted from Camusçu [14]

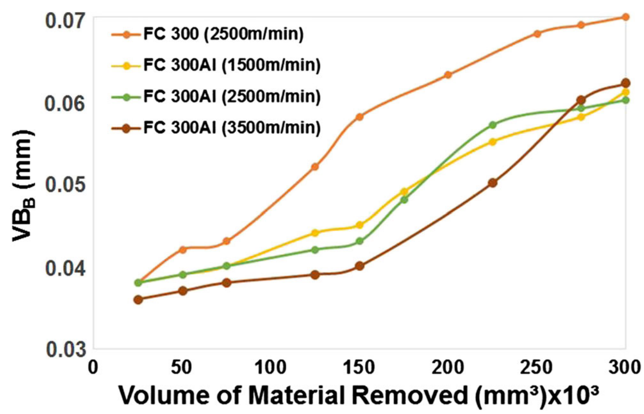


Fig. 16 Tool flank wear versus removed material. Adapted from Liu [81]

formation of a layer with a high concentration of inclusions of MnS from the workpiece material on the tool rake face of the tool. Although the reduction of the machining force components contributes to the reduction of tool wear, the determining factor is the formation of a layer strongly adhered to the tool rake face. Liu [81], Sahm et al. [109], and Dahl and Hessman [22] also observed similar behavior, however, only at certain intervals or at very high cutting speeds. This behavior observed in the machining of gray cast iron is receiving attention due to the possibility of reducing production costs and increasing productivity.

When aluminum is added to the pearlitic gray cast iron FC300, referred to as FC300Al, the machinability of this material is significantly improved (Fig. 16). The addition of aluminum in the workpiece material results in increased amount of this element on the cutting tool rake face, forming a layer that protects the tool against severe wear. According to Liu [81], aluminum element may exist in the form of Al_2O_3, which is a hard and resistant material, forming a layer of the rake face, contributing to a reduction in the abrasive wear of the tool. This is probably one of the reasons for smaller tool wear when machining the material FC300Al at 2500 m/min than the FC300 at the same shear rate. Therefore, it is evident that the addition of aluminum in the work material improves the machinability of pearlitic gray cast iron [101]. On the other hand, the Al_2O_3 is known as thermal isolator [84, 113, 137], and this thin layer adhered on the rake face act as a thermal barrier, protecting the tool against the heat flow by conduction; hence, the whole tool tends to work at lower temperatures, as compared when the Al_2O_3 layer is not present.

In fact, the addition of aluminum and calcium in the production of CGI during deoxidation step, prior to magnesium injection, produce non-metallic inclusions of calcium aluminates and calcium silicate aluminates which are deformable in the machining process. When the aluminum and calcium components not added before the addition of magnesium, non-metallic inclusions of magnesium silicates and magnesium oxides are formed. Such inclusions do not deform during machining and therefore is harmful to machinability [71].

Tooptong et al. [136] have conducted dry turning experiments on flaked graphite iron (FGI) and compact graphite iron (CGI) using straight grade of cemented carbides uncoated and coated with TiCN/Al_2O_3/TN. In their studies, surprisingly, they found that using the uncoated cemented carbide the tool lives for the machining, the FGI was shorter than for the CGI but the opposite was found when using the coated cemented carbide tools. The results were based on flank and crater wears. The authors justified the unexpected results when using uncoated tools by an adhesion layer of work material observed on the flank and rake faces of the tools that protects them against wear in the machining of CGI. This adhesion layer was not observed when using the coated tools.

4 Trends

Based on the literature review and authors shop floor experience, one field that need to be extensively studied is the use of pCBN and PCD at cutting speeds above 2000 m/min, at least, in machining of cast irons. These tools will only be applicable in case the friction coefficient is drastically reduced and consequently the heat generation and temperature can stay at low levels, eliminating or reducing the diffusion wear mechanism. It should be real in case of the new coatings generation applied to pCBN tools (with very sharp cutting edges), with no chemical affinities for the work material. Moreover, for both the PCD and pCBN tools, extremely sharp cutting edges (cutting edge radius < 100 μm) and in addition of using a cutting fluid, which is able to keep the cutting temperature at low values are really a promising attempt for the machining of this important group of work material. Cryogenic machining using CO_2 (temperature from −80 to −85 °C, or LN_2 with temperature around −195.8 °C) are important technologies that could guarantee very high productivity rates, but detailed investigation is necessary before this application can be considered feasible and dominated.

Another kind of tool that needs to be well investigated for cast iron machining is the coated pCBN (H and L), due to the expectation of the thin-coated layer acting to reduce the friction coefficient, and consequently the heat generation and the chip-tool interface temperature. The pCBN-L tools tend to have more toughness than the pCBN-H and can be thought as an alternative application in interrupted cuts, such as milling.

We believe that there is still a long way to go before machining of cast iron can be considered steadily dominated. Huge amount of studies and trials in different approaches are still necessary to approximate to this point. This involves the stiffness of the machine tools; improvements in the tool materials and tool design; and use of efficient cutting fluids, that besides being technically effective, they always have to be environmentally and human friendly, in other words, thinking hardly on the sustainable manufacturing.

5 Final remarks

Based on the intense background from the study conducted, the following conclusions can be highlighted:

In general, the cast irons are materials considered relatively easy to machine, particularly when considering the chip type/morphology, the cutting forces and power consumption are the machinability criteria.

White cast iron and CGI are not so easy to machine though, due to their high mechanical properties and presence of hard carbides in their microstructures that contribute to promote abrasive wear and consequently reduction in the tool life. The same behavior takes place with the gray cast iron machining, however, at lower level when compared with white and CGI cast irons.

Nodular cast iron has low machinability when the chip breakability is the criteria due to the frequently continuous chip formation.

Coated cemented carbide still remains the main tool material used for machining cast irons, in general, due to the good combination of hardness, toughness, and costs.

Ceramics and pCBN tool materials are interesting alternatives when high productivity, improved surface roughness, and dimensional tolerances are required because of the high cutting speed possible, ordinarily between 500 and 2000 m/min or faster.

Cast irons are ordinarily machined without the use of cutting fluids, particularly the gray cast irons. However, when machining white cast iron or CGI, due to the extremely high heat generation, a cutting fluid with good coolant ability is frequently recommended.

Although being a group of material that is considered relatively easy to machine, further detailed studies are needed in order to have the machinability of these materials steadily dominated.

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