CIRP Journal of Manufacturing Science and Technology 5 (2012) 87–101

Contents lists available at SciVerse ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Modeling the effect of compacted graphite iron microstructure on cutting forces and tool wear

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ARTICLE INFO

Article history:
Available online 28 April 2012

Keywords:
Compacted graphite iron
Finite element
Machining
Tool wear
Cutting forces

ABSTRACT

The characteristic mechanical (and physical) properties of compacted graphite iron (CGI) are contingent upon its unique microstructure. To model and simulate compacted graphite iron (CGI) in machining meaningfully, the metal's microstructure should not be overlooked throughout the process.

In this work, modeling the microstructure of CGI in machining is implemented using a commercial general-purpose finite element package; ABAQUS/EXPLICIT (v 6.8). Segmental chip is modeled by the introduction of a new chip formation modeling technique. The cohesive zone elements are used to model the graphite–matrix interface. The methodology pursued to implement the finite element model is based upon an iterative interaction between comprehensive metallurgical investigations and finite element formulation of the problem in hand. Metallurgical examination of fractured and machined chips is not solely performed as a tool of validation, but rather as a tool of modeling.

Vital model inputs are based upon metallurgical investigations of fractured CGI samples and machined chips. Subsequent comparisons between (1) simulated chips and (2) cutting forces trends, to experimental findings are used to validate the finite element model. The effects of cutting forces and temperature are comprehensively investigated to elaborate on their effects on tool wear. The effect of cutting speed (and feed rate) on cutting forces and cutting temperature determine the type of tool wear in CGI machining. Variation of the cutting speed triggers the deviation from mechanical to thermal tool wear mechanisms. This behavior is captured through the investigation of the cutting forces and simulated temperature trends in the finite element model. Other important findings are documented to serve as an optimization technique for tool material selection and machining conditions of compacted graphite iron (CGI) for which automotive and locomotive industries are of significant need to date.

1. Introduction

Cast irons are characterized by their wide range of achievable mechanical (and physical) properties and their competitive prices compared to other materials in most industries. Cast irons, in general, constitute of iron matrix (pearlite, ferrite, austenite, etc.), graphite, and smaller percentages of other additives. Gray cast iron (GCI),[1] compacted graphite iron (CGI), and nodular graphite iron (NGI)[2] are types of cast irons which primarily differ in their mechanical and physical properties, dictated by the shape, size, and growth mechanism of graphite in their microstructures.

The morphology of graphite whether is flaky, compacted, or nodular has a vital influence on determining the mechanical (and physical) properties of cast iron having the same metal matrix [1]. As graphite (free carbon) is several orders of magnitude more thermally conductive than the iron matrix, the thermal conductivity of cast iron is strongly influenced by the morphology, amount, and distribution of graphite within the matrix [2]. In gray cast iron (GCI), the flaky shaped interconnected graphite particles have a dominant tendency to grow in the basal plane direction (*A*-axis direction) [3]. The low *van der Waal*'s basal planes bonding forces are responsible for the low modulus of elasticity in flake graphite[3] [4]. On the other hand, the thermal conductivity in the basal plane direction is several folds higher than in the perpendicular direction in the graphite crystal [5]. Flaky graphite functions as excellent heat transport conduits leading to excellent thermal conductivity and accordingly lower thermal distortion of gray cast iron (GCI). However, flaky graphite particles act as internal notches in the form of stress concentration regions within

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[1] Gray iron (GI) or gray cast iron (GCI) is sometimes referred to as flake graphite iron (FGI).

[2] Nodule graphite iron (NGI) is also known as spheroid graphite iron (SGI).

[3] C_{1212} is as low as 0.018×10^4 MPa, where C_{1212} is the stiffness tensor parallel to the graphite crystal basal plane.

1755-5817/$ – see front matter © 2012 CIRP.
doi:10.1016/j.cirpj.2012.03.002

the matrix [6]. This promotes crack initiation and propagation leading to the gray iron's pseudo-brittle behavior and little plastic deformation prior to fracture.

Graphite in nodular graphite iron (NGI) is characterized by its isolated nodular (spheroid) graphite particles providing better ductility and higher overall strength compared to gray cast iron (GCI). One disadvantage of nodular graphite is its inferior thermal conductivity due to its isolated distribution in the metal matrix. In addition, the distinct growth mechanism of nodular graphite predominantly in the prismatic plane direction (*C*-axis) has an adverse effect on its thermal properties. Thermal conductivity in the prismatic plane direction (*C*-axis) is reported as one-hundredth times of it in the basal plane direction (*A*-axis) [5]. Accordingly, the superior strength of nodular graphite iron (NGI) comes on the expense of its inferior thermal properties.

On the other hand, compacted graphite iron's (CGI) mechanical (and physical) properties are intermediate between gray and nodular graphite irons. Graphite in compacted graphite iron (CGI) is more of coral-like stumpy with irregular boundaries and interconnected only within each eutectic cell. The irregular graphite–matrix interface results in an intimate adhesion between the graphite and the metal matrix producing more resistance to crack initiation and more vermiculate paths to crack propagation. Furthermore, the coral graphite particles with round edges serve as crack arrestors once cracks are initiated. This unique morphology of graphite in compacted graphite iron (CGI), thereafter, pays off in higher tensile strength, improved ductility, and higher modulus of elasticity. The results of fracture toughness tests published by Shen-Chih and Yin-Bean indicated that for the same matrix microstructure, compacted graphite iron with higher vermicularity[4] yielded low K_{IC} values, however these values were still higher than those of gray cast iron [6]. Furthermore, the interchanging growth directions mechanism of graphite in compacted graphite iron results in intermediate thermal properties and accordingly lower thermal distortion compared to nodular graphite iron (NGI) [7].

Compacted graphite iron (CGI) characteristic combination of double the ultimate strength, intermediate thermal conductivity, higher modulus of elasticity, and superior crack initiation and propagation resistances compared to gray cast iron (GCI), as well as better thermal conductivity and greater resistance to thermal distortion compared to nodular graphite iron (NGI) result in praised overall performance and higher demand [8,9]. Such "attractive" overall performance has presented compacted graphite iron (CGI) as a promising engine block candidate material to replace gray cast iron and aluminum alloys in the automotive industry. However, the relatively poor machinability of compacted graphite iron (CGI) to smoothly replace gray cast iron (GCI) in mass production lines without significant modification of the machining procedure is a significant hurdle until today [10–12].

The superior machinability of gray cast iron (GCI) compared to compacted graphite iron (CGI) is referred to the formation of a protective and lubricating layer of manganese sulfide (MnS) on the cutting tool surface when gray cast iron is machined [8,13]. Such layer was found to grow denser when gray cast iron (GCI) was machined at relatively high cutting speeds (800 m/min) in continuous cutting (turning/boring) [14]. The higher percentage of sulfur in gray cast iron (GCI) (0.08–0.12%) compared to it in compacted graphite iron (CGI) (0.005–0.025%) was basically the promoter of the formation of such layer. In addition, as magnesium is a strong sulfide former, abrasive magnesium sulfide inclusions were found to form preferentially to manganese sulfide in compacted graphite iron (CGI) leading to more cutting insert wear [8].

Aside from the absence of the protective and lubricating layer of manganese sulfide (MnS) in CGI machining, the presence of titanium in CGI poses a quite severe effect on tool wear. Large amounts of titanium (0.1–0.25%) is commonly used to control the formation of compacted graphite particles by increasing the stable range of magnesium in CGI production. Despite that titanium is typically present in all cast irons (0.005–0.02%), higher percentage of titanium in compacted graphite iron (CGI) promotes the formation of titanium carbonitride (TiCN) inclusions which are harder than tungsten carbide leading to more tool wear. It was found that a slight increase of trace level of titanium from 0.01 to 0.02% was sufficient to reduce the tool life by about 50% [8]. Other CGI manufacturing techniques are available in literature [15].

Machinability studies conducted by Moecellin et al. on different compacted graphite iron (CGI) grades lead to the development of a CGI grade providing a tool life of 83% relative to grade 250, hardness 214/223 HB, and 97/100% pearlite gray cast iron (GCI) [16]. The tests were performed using 10 mm diameter solid carbide drills from class K35, TiAlN single layer coated (3000 HV). However, the reported data were valid for drilling only and may not be applicable to other machining processes as admitted by Moecellin.

Other ways to deal with the relatively poor machinability of CGI were by proposing rotary insert tools hoping to have a material removal volume that was comparable to gray cast iron [17], or by using coated/uncoated different cutting insert materials [18], or by employing laser-assisted machining (LAM) technique at low speeds (102 m/min) [19].

However, all the up to date proposed solutions seemed to relatively work at either low cutting speeds, or for specific CGI matrix composition of low mechanical properties, or by using expensive and specialized cutting tools. Despite the many efforts to improve CGI's machinability to a level that is comparable to gray cast iron (GCI), it is evident that much work needs to be invested to reach this target.

Accurate analytical models are too complex or too simplified causing invalidity when large deformation, high strain rate, substantial temperature rise, with complex loading conditions are combined during machining. On the other hand, experimental techniques are inherently configuration-specific and very expensive for modeling complex machining processes. Aside from the expensive experimental efforts for machinability study, numerical techniques have proven to provide reasonable accuracy and reduced time and resources since *Klamecki* in 1973 to date [20].

In this work, study of tool wear and force measurement are performed in parallel with the finite element modeling procedure, and employed as validation tools. Since the microstructure of compacted graphite iron is the main player controlling the material's behavior relative to the other two irons (GCI & NCI), special attention is allocated to CGI's microstructure in the current work. Modeling and simulating the microstructure of compacted graphite iron in machining is the main focus in the current work to further consider the model as an optimization technique in the future. The methodology used in this work is based on comprehensive metallurgical investigations to validate the finite element model. Some of the finite element model inputs have been based on compacted graphite iron fracture tests at high strain rate [21]. The results of this methodology have been justified by experimental findings and presented in the results and discussion section.

2. Finite element modeling of compacted graphite iron

2.1. Modeling of compacted graphite iron matrix

Light microscope images of CGI samples are imported for image processing to exclude sample preparation imperfections such as

[4] Vermicularity is defined as the percentage of the graphite existing in the vermicular form when the graphite aspect ratio is between 2 and 10. Nodular iron would have an aspect ratio of 1, gray iron would have a aspect ratio of over 10.