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ScienceDirect

Procedia CIRP 58 (2017) 555 – 560

www.elsevier.com/locate/procedia

16th CIRP Conference on Modelling of Machining Operations

Simulation studies of turning of aluminium cast alloy using PCD tools

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Abstract

This study investigates the influence of cutting parameters on longitudinal turning of high Silicon cast aluminium alloy AlSi9Cu3 using PCD tools with and without chip breaker geometry. In order to build the 3D numerical model, the experimental and predicted cutting forces were used for inverse calibration of the Johnson-Cook material model which was implemented in DEFORM^{TM} finite element software. A sensitivity analysis has been performed in order to obtain an acceptable prediction of the machining parameters such as chip geometry and cutting forces as well as to understand the influence of friction and mesh size effects in the predicted results. Results have shown a satisfactory correlation between experimental turning data and numerical estimates based on assumptions that have been taken for the material behaviour.

Keywords: AlSi9Cu3 alloy; PCD inserts; Chip breaker; Numerical Simulation; Johnson-Cook model; Cutting forces; Chip geometry.

1. Introduction

AlSi9Cu3 is a very common and widely used aluminium alloy. This material offers excellent performance for a variety of weight reduction applications in aerospace, automotive and marine equipment. It features good castability, machinability and excellent mechanical properties. Components are generally produced by casting or forging to obtain near-net-shape geometries for lower costs that are posteriorly submitted to conventional machining processes in order to reach their final shape [1,2]. Given the large content of Silicon and the high chemical reactivity of aluminium, tool wear increases significantly which demands the usage of Polycrystalline Diamond (PCD) tools [3]. Additionally, PCD turning inserts enable an increase in material removal rate and surface integrity. However, due to the commonly obtained continuous chip geometry in turning operations [4], it is still necessary to design cutting tool inserts with chip control geometry for different workpiece materials under diverse cutting conditions. Even though a wide range of grooved chips can be found for WC inserts that is not verified for PCD inserts. The difficulty in obtaining similar geometries for PCD lied in the lack of precise and smooth surface manufacturing processes capable of accurately shape the inserts with the desired grooves. Due to the development of micro-cutting laser technology, such problem is minimized and multiple shapes of chip-breaking grooves can be generated nowadays [5], creating an emphasis on finding optimal geometries according to different purposes.

The design of chip breaker geometries able to ensure a specific chip flow and control breakage often consisted of expensive and long-winded trial-and-error approaches and, more recently, of analytical models and knowledge-based approaches which reveal to lack robustness, reliability as well as a limited application range [6,7,8].

Numerical simulation appears, therefore, as the most appropriate solution for addressing the design complexity. Three-dimensional FEM simulations allow an adequate and efficient chip breaker representation as well as its analysis, from the viewpoint of the optimum cutting tool geometry design, avoiding the costly production of PCD chip breaker trials. In addition, numerical models allow further insight into the cutting process: the prediction of cutting forces, contact pressure, temperature field and chip morphology may be used in order to

doi:10.1016/j.procir.2017.03.270

produce more efficient tools and provide feedback on tool life and the degree of machinability of a certain operation.

One key aspect of the numerical simulation of metal cutting process is the correct calibration of the material constitutive model. Severe plastic deformation through shear plane under high strain rates and temperature tends to make the direct material characterization extremely challenging which often prevents the implementation and analysis of metal cutting numerical simulations. Therefore, inverse identification of the material parameters is frequently used as an alternative approach to obtain adequate constitutive model calibration and can be used for performing predictive simulations [9,10,11].

In this paper, numerical simulation of longitudinal turning operations is performed using DEFORM™ software, by means of both 2D and 3D models. Two different PCD inserts have been used, one with flat rake face for inverse material calibration and other with a chip breaker geometry suitable for turning operations. Numerical models were validated with available experimental data. A numerical sensitivity analysis is also conducted regarding numerical mesh and friction parameters. Due to being relevant machinability indicators, main cutting force evolution and chip geometry are both compared between numerical and experimental results.

2. Experimental Procedure

2.1. Experimental apparatus

Experimental tests were performed under dry cutting conditions using a 5.9kW EFI-DU20 conventional horizontal lathe with a maximum spindle speed of 2500 rpm at the Faculty of Engineering, University of Porto. Regarding instrumentation, a KISTLER 9257B piezoelectric dynamometer was used along with a KISTLER 5007 amplifier and the HBM Spider 8 acquisition system for cutting force measurements. Figure 1 exhibits the experimental setup. Different cutting parameters combination was set for each turning test: two different speed ranges were considered as well as two distinct depths of cut ($\boldsymbol{a_p}$) and feed rates ($\boldsymbol{f}$), according to Table 1 [12].

Fig 1. Experimental setup of the longitudinal turning tests.

Table 1. Cutting parameters used in the experimental turning tests.

$\boldsymbol{n}$ [rpm]	$\boldsymbol{f}$ [mm/rev]	$\boldsymbol{a_p}$ [mm]
900; 2500	0.05; 0.25	0.25; 1.5

2.2. Workpiece material

AlSi9Cu3 specimens were obtained by permanent mould casting process and posteriorly machined to a diameter of ∅55 mm for appropriate surface and dimensional quality. In order to conduct a microstructure analysis, a material sample was prepared, polished and examined on the microscope (see Fig. 2). Table 2 compares the AlSi9Cu3 chemical composition of the alloy used in this paper and the NP EN 1706 standard [13] chemical composition for the proposed material.

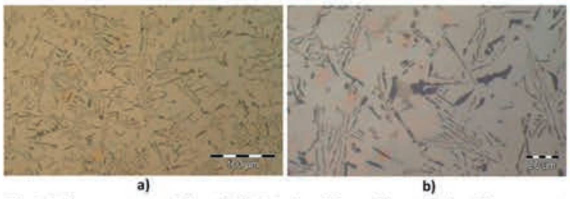


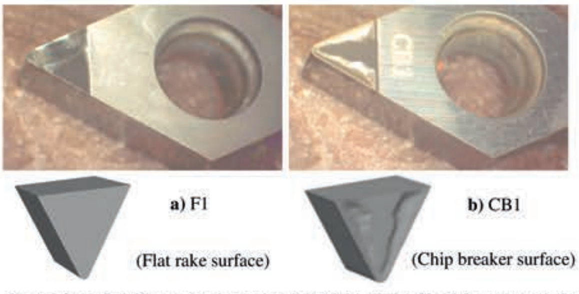
Fig 2. Microstructure of the AlSi9Cu3 aluminium alloy used in this paper: a) α-Al solid solution and Al-Si eutectic, Si in acicular shape; b) presence of Cu-rich and Fe-rich.

Table 2. Chemical composition of the AlSi9Cu3 alloy.

	Si	Fe	Cu	Mn	Mg	Ni	Pb	Ti	Al
NP EN 1706	8.0-11.0	1.3 max	2.0-4.0	0.55 max	0.05-0.55	0.55 max	0.35 max	0.25 max	Remaining
This paper	9.88	0.16	3.35	0.01	0.14	0.01	0.02	0.05	

2.3. Tools

Two distinct PCD turning inserts were used (see Fig. 3), one with a flat rake face and the other one with a chip breaker geometry, both from MAPAL cutting tools manufacturer. The inserts have a rhombic shape with a 55° tool tip angle, a clearance angle of 7° and a tool tip radius of 0.4mm. Chromatic confocal microscopy technique was successfully applied and allowed scanning of the inserts in three-dimensional space. The non-contact point sensor is a Stil Initial 4 from STIL with submicronic accuracy (capable of 130 µm resolution) that mounts directly on a coordinate measuring machine carriage to promote accuracy. For simplicity, only tool tip region was built, capturing both clearance and rake surface for F1 and CB1 inserts. PCD material is defined in DEFORM™ and was attributed to the tool in the numerical simulation.



a) F1

(Flat rake surface)

b) CB1

(Chip breaker surface)

Fig 3. MAPAL PCD turning inserts: a) DCGW 11T304 F01N-0AA (where F1); b) DCGT 11T304 F01N-C1A (where CB1).