Measurement 45 (2012) 344–353

Contents lists available at SciVerse ScienceDirect

Measurement

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

Analysis of surface roughness and cutting force components in hard turning with CBN tool: Prediction model and cutting conditions optimization

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ARTICLE INFO

Article history:
Received 16 June 2011
Received in revised form 15 October 2011
Accepted 17 November 2011
Available online 2 December 2011

Keywords:
Hard turning
AISI H11 steel
CBN
Cutting parameters
ANOVA
RSM

ABSTRACT

In this study, the effects of cutting speed, feed rate, workpiece hardness and depth of cut on surface roughness and cutting force components in the hard turning were experimentally investigated. AISI H11 steel was hardened to (40; 45 and 50) HRC, machined using cubic boron nitride (CBN 7020 from Sandvik Company) which is essentially made of 57% CBN and 35% TiCN. Four-factor (cutting speed, feed rate, hardness and depth of cut) and three-level fractional experiment designs completed with a statistical analysis of variance (ANOVA) were performed. Mathematical models for surface roughness and cutting force components were developed using the response surface methodology (RSM). Results show that the cutting force components are influenced principally by the depth of cut and workpiece hardness; on the other hand, both feed rate and workpiece hardness have statistical significance on surface roughness. Finally, the ranges for best cutting conditions are proposed for serial industrial production.

1. Introduction

CBN tools are widely used in the metal-working industry for cutting various hard materials such as high-speed tool steels, die steels, bearing steels, case-hardened steels, white cast iron, and alloy cast irons. In many applications, cutting of ferrous materials in their hardened condition can replace grinding to give significant savings in cost and productivity rates [1–3]. Hard turning process differs from conventional turning because of the workpiece hardness, the required cutting tool, and the mechanisms involved during chip formation. Whenever machining given parts straightforwardly after they have been hardened, hard turning offers a number of potential advantages over traditional grinding, including lower equipment costs, shorter setup time, fewer process steps, greater part geometry flexibility, and usually there is no need cutting fluid use. If hard turning could be applied to fabricate complex parts, manufacturing costs could be reduced by up to 30 times [4].

Many studies have been conducted to investigate the performance of CBN tool in the cutting of various hardened materials. Özel and Karpat [5] used regression and artificial neural network models for predicting the surface roughness and tool wear in hard turning of AISI H11 steel using CBN inserts. Bouacha et al. [6] applied response surface methodology (RSM) to investigate the effect of cutting parameters on surface roughness and cutting force components in hard turning of AISI 52100 with CBN tool. The results show how much the surface roughness is influenced by both feed rate and cutting speed, and that the depth of cut exhibits maximum influence on the cutting forces

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doi:10.1016/j.measurement.2011.11.011

Nomenclature

ap	depth of cut (mm)	*Ra*	surface roughness (μm)
f	feed rate (mm/rev)	*t*	cutting time (min)
Fa	feed force (N)	*Vc*	cutting speed (m/min)
Fr	thurst force (N)	α	clearance angle (°)
Fv	tangential force (N)	γ	rake angle (°)
H	workpiece hardness	λ	inclination angle (°)
HRC	rockwell hardness	χ	major cutting edge angle (°)

as compared to feed rate and cutting speed. Sahin and Motorcu [7] developed the surface roughness model using surface methodology when machining hardened AISI 1050 steel. They reported that CBN cutting tools produced a better surface roughness than those of KY1615 (uncoated ceramic) cutting tools in most experimental conditions. Grzesik and Wanat [8] investigated the surface finish generated in hard turning of quenched alloy steel using conventional and wiper ceramic inserts. They concluded that surfaces produced by wiper contained blunt peaks with distinctly smaller slopes resulting in better bearing properties. Matsumoto et al. [9] and Thiele and Melkote [10] studied the effect of workpiece hardness on residual stress distribution. In a recent study, Guo and Liu [11] investigated material properties of hardened AISI 52100 bearing steel using temperature controlled tensile tests and orthogonal cutting tests and hence; they demonstrated that hardness greatly influences the material cutting process. When using alumina–TiC ceramic tools, Benga and Arabo [12] and Kumar et al. [13] observed a better surface quality in turning of hardened steel components. Lima et al. [14] analyzed the effects of cutting speed, feed rate and depth of cut on cutting forces and surface roughness in hardened AISI 4340 high strength low alloy steel and AISI D2 cold work tool steel materials. Feng and Wang [15] presented an investigation for the prediction of surface roughness in finish turning operations by developing an empirical model considering various parameters: workpiece hardness, feed rate, cutting tool point angle, depth of cut, spindle speed, and cutting time. Methods, such as data processing techniques, non-linear regression analysis with logarithmic data transformation, were employed for developing the empirical model to predict the surface roughness. Suresh et al. [16] focused on machining mild steel and TiN-coated tungsten carbide (CNMG) cutting tools for developing a surface roughness prediction model using response surface methodology (RSM). Genetic algorithms (GAs) were also used to optimize the objective function and compared with RSM results. It was observed that GA program provided minimum and maximum values of surface roughness and their respective optimal machining conditions. Neseli et al. [17] have applied response surface methodology (RSM) to optimize the effect of tool geometry parameters on surface roughness in the case of the hard turning of AISI 1040 with P25 tool.

In this paper, an experimental contribution that focuses on prediction and optimization of both surface roughness and cutting force components during hard turning of AISI H11 steel with a cubic boron nitride (CBN 7020) cutting tool is presented. The ANOVA study involves the effects of cutting parameters (cutting speed, feed rate and depth of cut) coupled with workpiece hardness.

2. Experimental procedure

2.1. Workpiece and tool materials

Turning experiments were performed in dry conditions using a universal lathe type SN 40C with 6.6 kW spindle power. The workpiece material was AISI H11, hot work steel which is popularly used in hot form pressing. Its resistance to high temperature and its aptitude for polishing enable it to answer most requests for hot dieing and molding under pressure. Its chemical composition (in wt.%) is given as: C 0.35; Cr 5.26; Mo 1.19; V 0.50; Si 1.01; Mn 0.32; S 0.002; P 0.016; Fe 90.31 and other components 1.042. The workpiece was through-hardened followed by a tempering process to attain three different hardness levels, namely 40; 45 and 50 HRC (Rockwell hardness). Its hardness was measured by a digital durometer (DM2-D 390). Details of the thermal treatment process are given in Table 1.

The cutting insert is a removable type and offered eight squared working edges. The chosen CBN tool in commercially known as CBN7020 and it is essentially made of 57% *CBN* and 35% Ti(C, N). Its standard designation is SNGA12 04 08 S01020 and it is manufactured by Sandvik company. The physical properties are summarized in Table 2.

Tool holder is codified as PSBNR 25 × 25 K12 with a common active part tool geometry described by $\chi_r = +75°$, $\lambda = -6°$, $\gamma = -6°$ and $\alpha = +6°$.

The three components of the cutting forces; feed force (*Fa*), thrust force (*Fr*) and tangential force (*Fv*), schematically shown in Fig. 1, were recorded using a standard quartz dynamometer (Kistler 9257B) allowing measurements from −5 to 5 KN. Instantaneous roughness criteria measurements (arithmetic mean roughness, *Ra*), for each cutting condition, are obtained by means of a Mitutoyo

Table 1
Heat treatment process for AISI H11.

Workpiece hardness	Temperature (°C)	
	Temper	Quench
~50 HRC	~[1025 ÷ 1050]	~[570 ÷ 585]
~45 HRC		~[600 ÷ 620]
~40 HRC		~[620 ÷ 650]