Tribology International 104 (2016) 140–156

Contents lists available at ScienceDirect

Tribology International

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

Milling tool's flank wear prediction by temperature dependent wear mechanism determination when machining Inconel 182 overlays

Chengdong Wang [a,*], Weiwei Ming [b], Ming Chen [b]

[a] Research Institute of Advanced Manufacturing Technology, School of Mechanical and Electric Engineering, Soochow University Suzhou 215021, China
[b] State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University Shanghai 200240, China

ARTICLE INFO

Article history:
Received 14 June 2016
Received in revised form
26 August 2016
Accepted 28 August 2016
Available online 30 August 2016

Keywords:
Milling tool's flank wear
Threshold temperature
Worn surface
Wear mechanism

ABSTRACTS

Inconel 182 overlays is popular for its advantageous mechanical and chemical properties at elevated temperature, which is widely used as anti-corrosion material deposited on cast seal surface of nuclear steam turbine. The Inconel overlays deposited on the complicated shape of cast seal requires further milling process to obtained high quality surface. However, Inconel 182 overlays is a typical difficult to cut material due to its low thermal conductivity, plastic deformation and severe adhesion, which result in catastrophically tool wear. Therefore, it is necessary to establish a milling tool wear model to predict actual tool wear so as to save tool costs. Unfortunately, the existing tool wear models are all established to predict tool wear in continuous turning process, not suitable for the interrupted milling process. To solve this problem, this paper firstly determines the threshold temperature of adhesive wear, diffusive wear and oxidative wear of the cemented carbide and its basic TiAlN or TiN coating against Inconel 182 overlays by sliding wear tests, which is the emergence criterion of different tool wear mechanism. Based on the above wear mechanism determination, a mathematical model of milling tool's flank wear is then proposed by acquisition of the real time cutting force and temperature. The results show that the errors of the predicted minimum values are all within 10%, demonstrating that this model can be used to predict the milling tool's flank wear when machining Inconel 182 overlays.

1. Introduction

As nuclear steam turbines are working in saturated wet steam environment, its critical components such as seal at intake port or exhaust port of cast suffers corrosion and erosion, resulting in rotor damage. The use of anti-corrosion material deposited on steam seal then machined to the required thickness with specific surface quality can be an effective and economical way to prevent this failure. Reasonable selection of this anti-corrosion material not only saves deposited material, but also can improve its service life.

Nickel-based alloys are famous for its superior mechanical and chemical properties including excellent resistance to corrosion, erosion and thermal stability even at elevated temperature [1]. Among them, Inconel 182 is a typical filler material, widely employed as overlays covering on critical components of nuclear steam turbine, as shown in Fig. 1. However, it is an extremely difficult to cut material due to its low thermal conductivity, plastic deformation and intense friction between tool and workpiece, which pose a considerable challenge during the machining [2,3].

Under this extreme heat and force coupled situation, cutting tool are prone to suffer excessive abrasive wear, adhesive wear, diffusive wear and oxidative wear if the lubrication strategy or tool material are not properly employed [4,5]. Dry machining leads to increased cutting temperature, which introduce higher wear rate, therefore, Minimum Quantity Lubrication (MQL) can be the promising green lubrication strategy [6]. Tool material for machining nickel-base alloys are usually ceramic and carbide. Although ceramic tools seems suitable for high speed cutting due to its good abrasion resistance, excellent anti-adhesion and high temperature chemical stability [7], however, its impact resistance is poor, it chips catastrophically when machining the non-uniform or irregular workpiece such as Inconel overlays on steam turbine cast. Cemented carbide is an alternative tool material to machine nickel-base alloys and its coating performance is a decisive factor of reducing the friction or hindering cutting heat between tool and workpiece [8]. The basic coatings are titanium matrix of TiN and TiAlN [9]. Many researchers have studied their tribology properties against SiO_2 ball [10,11], but their threshold temperature of different wear mechanism including adhesive wear, diffusive wear or oxidative wear against Inconel 182 overlays is not yet determined. It means that the cemented carbide tool's failure types can be not

* Corresponding author.
E-mail address: wangchengdong99@163.com (C. Wang).

http://dx.doi.org/10.1016/j.triboint.2016.08.036
0301-679X/

Nomenclature

A_c	cross section area of chip [cm^2]
A_s	cross section area of shear plane [cm^2]
a_c	chip depth [mm]
a_w	chip width [mm]
a_e	width of cut [mm]
a_p	depth of cut [mm]
f	feed rate [mm/min]
F_s	shear force [N]
F_r	radial force [N]
F_f	normal force [N]
F_t	tangential force [N]
F_n	maximum normal force [N]
H	hardness [HV]
J	diffusion flux [l/(m^2s)]
L	sliding distance [m]
P	normal load [N]
Q	apparent activation energy [J/mol]
R	universal gas constant [J/Kmol]
T_c	cutting temperature [°C]
T_{flank}	tool flank temperature [K]
t	actual cutting time [min]
Δm	mass loss [mg]
VB	flank wear land width [mm]
v_c	cutting speed [m/min]
v_s	sliding velocity [m/min]
w	wear [mm]
w_M	mechanical wear [mm]
w_T	thermal wear [mm]
W_r	wear rate [$mm^3/(N\cdot m)$]
σ_s	yield stress [MPa]
α_0	clearance angle [°]
β	friction angle [rad]
γ_0	rake angle [°]
θ	milling phase angle [rad]
μ	friction coefficient
ρ	density [g/cm^3]
τ	shear stress [MPa]
φ	shear angle [rad]

clearly divided, not to mention the precisely predicting or controlling the tool wear when machining the difficult to cut Inconel 182 overlays.

Tool wear monitoring and prediction are hot topics. The methods of tool wear monitoring can be divided into direct or indirect. Direct tool wear monitoring such as vision or optical observation are usually impossible to perform due to the continuous cutting and presence of coolant and chips. However, indirect tool wear monitoring can be attained by using suitable sensors of monitoring forces [12–15], vibrations [16–18] and acoustic emission [19–22]. The common tool wear prediction models can be divided into empirical model, finite element model and mathematical model. Taylor tool life model is the typical empirical model (ISO 3685 for turning and ISO 8688 for milling). It can predict the tool life at various cutting parameters once the coupling coefficient is determined. However, it cannot present real amount of wear at arbitrary cutting time as the tool wear is a time dependent process. Finite element model is also an effective tool wear prediction method. Many researchers have used the Deform 3D codes to forecast tool crater wear in turning process [23–25]. However, it cannot predict tool wear in the interrupt milling process and the built-in mathematical model is relative simple (Archard or Usui model), which cannot simulate the tool wear under multiple wear mechanism. To understand the different wear mechanism including abrasion, adhesion and diffusion, several tool wear mathematical models are established by researchers, which is listed in Table 1. Among them, Luo's tool wear mathematical model comprehensively considers the abrasive wear, adhesive wear and diffusive wear. It supposes that total wear is the sum of mechanical and thermally activated processes, and the abrasive and adhesive processes are predominantly determined by cutting length, while thermally-activated diffusion and oxidation processes are determined by temperature [26]. Since the technological parameters including temperature, sliding velocity and normal force are described more precise, this model is more closely to reality [27].

Most of these mathematical tool wear models are proposed for continuous cutting process in dry cutting condition [28], few of them can be used for tool wear prediction in interrupt milling process under MQL. Since some variables in these wear models including sliding velocity, normal force are difficult to determined and the temperature dependent wear mechanism is not understood, it is still a challenge to predict milling tool's flank wear when machining the difficult to cut Inconel 182 overlays.

To overcome this problem, this paper firstly determines the threshold temperature of adhesive wear, diffusive wear and oxidative wear of cemented carbide tool and its basic TiAlN or TiN coating against Inconel 182 overlays by sliding wear tests, which is the criterion of tool wear mechanism determination. Then, an accurate mathematical model of milling tool's flank wear when machining Inconel 182 overlays is established by tool wear mechanism determination and real-time milling force acquisition. During the model establishment, Taylor regression is employed to fulfill the match of tool and workpiece, extending application range of this model at various cutting parameters combination.

2. Experiment details

2.1. Materials

Inconel 182 overlays, obtained by depositing Inconel 182 electrodes through shielded metal arc welding (SMAW), was employed as workpiece material. Our previous study shows that the microstructure and machinability of Inconel overlays are related to overlays thickness [3]. In order to eliminate the material property deviation, the Inconel overlays workpiece for both sliding wear tests and for milling tests are all cut from the same raw material at same overlay thickness ($\geq$ 8 mm) by Wire Electrical Discharge Machining (WEDM). The physical properties and the chemical composition of welded Inconel 182 overlays are illustrated in Tables 2 and 3, respectively.

The cemented carbide was employed as cutting tool material, whose physical properties is shown in Table 4. Due to the strong adhesion of Inconel 182 overlays, the uncoated cemented carbide wears severely [5]. To overcome this problem, the typical TiAlN or TiN coating were deposited separately on cemented carbide to improve the wear resistance. TiAlN coating and TiN coating were deposited by commercial arc evaporation system supplied by Oerlikon Balzers. The TiAl targets (2:1, purity 99%) mixed with N_2 (99.9% purity) were used for TiAlN coating while pure Ti mixed with N_2 (99.9% purity) were used for TiN coating. During the deposition process, the cemented carbide prepared as substrates were placed on a rotating substrate holder which rotated to obtain