Journal of Materials Processing Technology 214 (2014) 200–209

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Modeling of material removal rate and surface roughness in finishing of bevel gears by electrochemical honing process

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ARTICLE INFO

Article history:
Received 22 March 2013
Received in revised form 26 July 2013
Accepted 20 August 2013
Available online 7 September 2013

Keywords:
Modeling
Material removal rate
Surface roughness
Electrochemical dissolution
Electrochemical honing
Bevel gears

ABSTRACT

This paper describes mathematical modeling of material removal rate (MRR) and surface roughness of the bevel gears finished by the electro-chemical honing (ECH) process. Since, ECH hybridizes electrochemical dissolution (ECD) and mechanical honing therefore, contribution of ECD in MRR and surface roughness has been modeled using Faraday's law of electrolysis while contribution of mechanical honing has been modeled considering material removal as a phenomenon of uniform wear and using Archard's wear model. Formulations are also proposed for computing the surface area, required by these two models, along the inter-electrode gap (IEG) based on the geometry of the straight bevel gear tooth surfaces. The developed models were experimentally validated using an indigenously developed experimental setup for finishing of bevel gears by ECH based on an envisaged novel concept of twin complementary cathode gears. An aqueous solution containing 25% NaCl + 75% $NaNO_3$ was used as the electrolyte. The predicted values of MRR and surface roughness have shown close agreement with the experimental values. The experimental results, SEM images and bearing area curve have shown appreciable improvement in the surface roughness and surface integrity ensuring better operating performance of the gears finished by ECH within an optimized finishing time of 2 min.

1. Introduction

Gear is one of the essential machine elements used to transmit motion and power by the successive engagements of teeth on their periphery. Application areas for gears are diverse and include machine tools, automotives, aerospace, marine, oil and gas industry equipments, cement and other processing mills, steel processing units, etc. (Davis, 2005). The operating performance such as power transmission efficiency, noise, vibration and durability of the gears, depends on its surface finish and quality. To prevent failure of gears requires careful consideration of gear form accuracy, gear materials, gear tooth forces, lubrication, operating conditions, and surface quality which in turn depend on the gear finishing method. Form errors and surface roughness of gears can be reduced significantly by finishing processes (Jain et al., 2009). Generally used gear finishing processes for bevel gears namely gear grinding and gear lapping, have some limitations such as gear grinding is expensive, complicated and may produce undesirable effects such as grinding burn. Grinding burn damages the surface integrity of the ground workpiece and if it is not detected then loaded gear might fail with severe consequences like tooth breakage. Lapping is the oldest but still widely used process to finish the surface of the bevel gear tooth flanks and thus reducing the operating noise. It is a time consuming process and can correct only minor errors of the gear tooth profile. If lapping is used for longer duration, it may affect form of the gear teeth profile (Karpuschewski et al., 2008).

Electrochemical honing (ECH) hybridizes capabilities of electrochemical dissolution (ECD) and mechanical honing in one operation and is a potential promising alternative to the conventional gear finishing processes. Wei et al. (1986) mentioned that ECH has ability to improve surface finish as well as to correct form errors, smoothening of irregularities on the surface and being productive at the same. ECH can achieve average surface roughness values up to 0.05 μm and dimensional tolerances up to ±0.002 μm (Benedict, 1987). It offers some unique features such as workpiece material of any hardness can be processed and less cycle time as compared to the existing processes. Misra et al. (2013) studied the effect of electrolyte composition on percentage improvement in bearing ratio by experimental runs conducted using the mixture D-Optimal design approach and found an aqueous solution containing 70% NaCl and 30% $NaNO_3$ as an optimum electrolyte composition.

Very few references are available on modeling of material removal rate (MRR) and surface roughness in the finishing of gears by the ECD based processes. Ning et al. (2011) developed a mathematical model for total thickness of the material removed and surface roughness in pulse electrochemical finishing (PECF) of spiral bevel gears and experimentally validated their models. But, they

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http://dx.doi.org/10.1016/j.jmatprotec.2013.08.010

Nomenclature

A_b	Area of the bottom land (mm^2)
A_f	Area of the tooth flank of the gear (mm^2)
A_r	Area of the fillet surface at root of the gear (mm^2)
A_s	Surface area of the bevel gear tooth where the electrolytic dissolution takes place through flow of current (mm^2)
A_t	Area of the top land (mm^2)
D_w	Working depth of gear tooth (mm)
E	Electrochemical equivalent of the workpiece material (g)
f	Factor used to convert the height of rectangle into height of a triangle with same area and the base length (=2)
F	Faraday's constant (=96,500 C)
F_n	Total normal load acting along the line of action (N)
F_w	Facewidth of the bevel gear (mm)
H	Brinell hardness number (BHN) of the workpiece material (N/mm^2)
h_e	Total thickness of material removed from the workpiece surface in one cycle of ECD (μm)
h_h	Total thickness of material removed from the workpiece surface in one cycle of honing (μm)
h_p	Distance between center line of the cathode surface roughness and the peaks on the workpiece surface before ECD (μm)
h_v	Distance between center line of the cathode surface roughness and the valleys on the workpiece surface before ECD (μm)
h'_p	Distance between center line of the cathode surface roughness and the peaks on the workpiece surface after ECD (μm)
h'_v	Distance between center line of the cathode surface roughness and the valleys on the workpiece surface after ECD (μm)
I	Amount of the current passed in the IEG (A)
J	Current density in the IEG (A/mm^2)
K	Wear coefficient
k	Factor that indicates proportion of total thickness of material removed from the valleys in one cycle of ECD and honing
K_e	Electrical conductivity of the electrolyte ($\Omega^{-1}\,mm^{-1}$)
L_i	Length of the involute profile (mm)
L_c	Length of chord of the involute (mm)
L_r	Length of arc of fillet at the root (mm)
MRR_{ECH}	Material removal rate in ECH (mm^3/s)
N_s	Number of revolutions of the workpiece gear per second (rps)
P	Perimeter of the workpiece gear (mm)
r	Radius of the involute arc (mm)
R_{zi}	Arithmetic mean of maximum peak-to-valley heights for the UNFINISHED workpiece surface (μm)
$R_{z_{ECH}}$	Arithmetic mean of maximum peak-to-valley heights for the ECHed workpiece surface (μm)
$R_{z_{ECD1}}$	Arithmetic mean of maximum peak-to-valley heights for the workpiece surface AFTER one cycle of ECD (μm)
$R_{z_{ECH1}}$	Arithmetic mean of maximum peak-to-valley heights for the workpiece surface AFTER one cycle of ECH (μm)
r_b	Radius of the base circle (mm)
S	Total sliding distance (mm)
t	Finishing time (s)
T	Number of teeth of the workpiece gear
V	Applied voltage (V)
V_e	Volumetric material removal rate (MRR) due to ECD (mm^3/s)
V_h	Volumetric material removal rate (MRR) due to honing action (mm^3/s)
W	Width at the base of the tooth (mm)
W_t	Width of top land (mm)
W_b	Width of bottom land (mm)
Y	Inter-electrode gap (mm)
α	Pressure angle of the involute profile
η	Current efficiency
ρ	Density of the anodic work material (g/mm^3)
θ	Angle subtended by the involute at its centre (deg.)
ΔV	Total voltage loss in the IEG (V)

finished one tooth at a time and reported improvement in the surface roughness and form errors. Ruszaj and Zybura-Skrabalak (2001) developed a mathematical model for MRR in the ECD with flat ended electrode and compared the theoretical results with the actual results. Park and Kahraman (2009) combined Archard's wear model with finite-element based contact model for simulation of surface wear of face-milled or face-hobbed hypoid gear pairs. Pavlov (2011) proposed computational methods for estimation of the wear, service life, and efficiency of the straight bevel gears having involute profile while Chernets and Bereza (2009) investigated on kinetics of wear of gear tooth and proposed a method for wear and durability of straight bevel gears.

From the review of the past work it is evident that no work has been reported on modeling of MRR and surface roughness of bevel gears finished by the ECH process. The objective of the present work is to bridge this gap. This paper describes development of the models of MRR and arithmetic mean of maximum peak-to-valley heights (R_z) for the flank surface of bevel gears finished by the ECH process and their experimental validation. These models have been developed as function of rotary speed of the workpiece gear and current in the inter-electrode gap (IEG), which indirectly takes into account the effects of other electrolytic parameters such as concentration, temperature and flow rate. Since, ECH hybridizes ECD and mechanical honing therefore, contribution of ECD in MRR and surface roughness has been modeled using Faraday's law of electrolysis while, contribution of mechanical honing has been modeled considering material removal by honing as a process of uniform wear and using wear model proposed by Archard (1953). Formulations are also proposed to compute the surface area along the inter-electrode gap (IEG) based on the geometry of the gear tooth surfaces of the straight bevel gears as required by these models. Comparison of the theoretical values with the experimental results has been done. These models and their experimental validation optimized the applied voltage and rotary speed which helps in performance optimization of finishing of gears by ECH.

2. Finishing of bevel gears by ECH

2.1. Working principle

Bevel gear finishing by ECH is much more difficult than finishing of cylindrical gears (i.e. spur or helical gears) due to their complex geometry which restricts feeding motion of the workpiece gear required for finishing its entire face width. This problem was resolved by envisaging a novel concept of twin complementary