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Julia Mazak

Method for Optimizing the Tool and Process Design for Bevel Gear Plunging Processes

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Method for Optimizing the Tool and Process Design for Bevel Gear Plunging Processes

Methode zur Optimierung der Werkzeug- und Prozessauslegung für Kegelradtauchprozesse

Von der Fakultät für Maschinenwesen
der Rheinisch-Westfälischen Technischen Hochschule Aachen
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Julia Mazak

Berichter:

Univ.-Prof. Dr.-Ing- Thomas Bergs
Univ.-Prof. Dr.-Ing. Dr.-Ing. E.h. Dr. H. c. Dr. h. c. Fritz Klocke

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Herausgeber:
Prof. Dr.-Ing. T. Bergs
Prof. Dr.-Ing. Dipl.-Wirt. Ing. G. Schuh
Prof. Dr.-Ing. C. Brecher
Prof. Dr.-Ing. R. H. Schmitt

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Wer immer strebend sich bemüht,
den können wir erlösen.

He who strives on and lives to strive
Can earn redemption still.

(Goethe, Faust II)

In memorian Ingrid Gerlofsma

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Abstract

For manufacturing bevel gears, a special tool system consisting of cutterhead and removable stick blades is used. This tool system produces multi-flank chips which are of complex, three-dimensional geometry. Therefore, the process and machine kinematics are subject to a sophisticated predefinition.

Existing, empirical wear models for bevel gear cutting are limited to discontinuous plunging. Furthermore, no validated, simulative process analysis for bevel gears exists so far. The objective of this thesis was to optimize the process for continuous and discontinuous plunging for bevel gear cutting regarding tool life based on tool angles and process parameters. For this purpose, a wear model was developed that is based on the elastic deformation of the workpiece and regards the thrust force. The influence of the rake angle on the thrust force was modelled by means of the shear angle.

First, it was investigated whether the planar-based penetration algorithm is suitable for determining the geometric-kinematic characteristics of plunging. The results of the planar-based penetration algorithms were plausible. The qualitative comparison of the simulated, undeformed chip geometry to actual chips of cutting trials was successful. The simulated chips matched the actual chips in both shape and proportions. For all processes, the deviation between the simulated flank and the target flank was below 1 µm.

In cutting trials, the influence of the varied process parameters and tool angles as well as the influence of the combination of these factors on tool wear was quantified. No clear basic mathematical relationship could be established for the results.

The developed model was applied to the results of the cutting trials combining feed ramp and tool angle variation. These results had not been used for determining the model parameters. The equivalence tests for the model results were successful, thus validating the model.

In order to find out which constraints there are for an application of the optimization method to continuous plunging, the model was transferred to a continuous plunging sample gear. Measured and simulated tool wear match and optimization potential for the investigated gear was presented.

Kurzzusammenfassung

Zur Herstellung von Kegelrädern kommen spezielle Werkzeugsysteme zum Einsatz, die aus einem Messerkopf und entnehmbaren Stabmessern bestehen. Aufgrund der komplexen, dreidimensionalen Geometrie der Zahnflanke folgt die zum Einsatz kommende Prozess- und Maschinenkinematik einer wohldurchdachten Festlegung.

Bestehende empirische Verschleißmodelle für das Kegelradfräsen beschränken sich auf das diskontinuierliche Tauchen. Weiterhin existiert bislang noch keine validierte, simulative Prozessanalyse für das Kegelradfräsen. Das Ziel dieser Arbeit ist die Prozessoptimierung für kontinuierliche und diskontinuierliche Tauchprozesse beim Kegelradfräsen hinsichtlich der Standmenge auf Basis der Werkzeugwinkel und Prozessparameter. Dazu wurde ein Verschleißmodell entwickelt, das auf der elastischen Verformung des Werkstücks basiert und die Drangkraft berücksichtigt. Der Einfluss des Spanwinkels auf die Drangkraft wurde anhand des Scherwinkels modelliert.

Zuerst wurde untersucht, ob die ebenen-basierte Durchdringungsrechnung für die Bestimmung der geometrisch-kinematischen Kennwerte für Tauchprozesse geeignet ist. Die Ergebnisse der ebenen-basierte Durchdringungsrechnung waren plausibel. Der qualitative Vergleich der simulierten unverformten Spanungsgeometrie mit reellen Spänen aus Zerspanungsversuchen war erfolgreich. Die simulierte Spanungsgeometrie entsprach sowohl in der Form als auch hinsichtlich der Proportionen den tatsächlichen Spänen. Für alle Verfahren lag die Abweichung zwischen der simulierten Flanke und der Zielflanke unter 1 µm.

In Zerspanversuchen wurden der Einfluss der variierten Prozessparameter und Werkzeugwinkel sowie der Einfluss der Kombination dieser Faktoren auf den Werkzeugverschleiß quantifiziert. Die Ergebnisse folgen keinen mathematischen Grundfunktionen.

Das entwickelte Modell wurde auf die Ergebnisse der Zerspanungsversuche mit kombinierter Vorschubrampe und Werkzeuggeometrie angewendet. Diese Versuchsergebnisse waren nicht zur Ermittlung der Modellparameter verwendet worden. Der Äquivalenztest für die Modellergebnisse war erfolgreich, wodurch das Modell validiert wurde.

Um Beschränkungen zu ermitteln, die bei der Anwendung der Optimierungsmethode für kontinuierliche Prozesse bestehen, wurde das Verschleißmodell anhand einer Beispielverzahnung auf einen kontinuierlichen Tauchprozess umgesetzt. Gemessener und simulierter Verschleiß stimmen gut überein und es wurde Optimierungspotential für den untersuchten Verzahnungsfall aufgezeigt.

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Symbols and Abbreviations

Formelzeichen und Abkürzungen

Latin

Latein

Symbol	Unit	Name
a	[µm]	Wear coefficient for break-in wear
a	[m^{-c}]	Experimental parameter of KÜHN model
a_1	[-]	Experimental parameter of CERETTI and KÜHN model
a_{ij}	[div.]	Parameters of GUTMANN model
a_e	[mm]	Cutting width for turning
a_p	[mm]	Cutting depth for turning
b	[mm]	Chip width of MERCHANT/ERNST model
b	[mm]	Tooth width
b	[mm]	Width of cut of GUTMANN model
b	[mm]	Width of flank wear in cross-section
b	[-]	Wear coefficient for steady-state wear
b_1	[-]	Experimental parameter of CERETTI model
b_i	[-]	Bin width
b^*	[mm]	Specific chip width
c	[-]	Experimental parameter of KAMM and KÜHN model
c	[ln(µm)]	Wear coefficient for failure region
c_1	[-]	Experimental parameter of CERETTI model
$c_{1...17}$	[-]	Experimental parameters of SCHALASTER model
d	[mm]	Tool diameter of DAMARITÜRK Model
d	[-]	Wear coefficient for geometry shape
$\bar{d}$	[-]	Arithmetic average of set difference
$d_{a,0}$	[mm]	Outside diameter of gear hob
d_i	[-]	Difference of set
e	[µm]	Rake face offset
f_z	[mm]	Feed per blade group
f_z	[-]	Number of teeth of DAMMER model

Symbol	Unit	Name
$\tilde{f}$	[-]	Value of density function
h	[mm]	Chip thickness for MERCHANT/Q model
h	[mm]	Depth of groove of RABINOWICZ model
h	[mm]	Profile height
h_0	[mm]	Undeformed chip thickness
h_1	[mm]	Deformed chip thickness
h_i	[-]	Relative frequency
h_{cu}	[mm]	Chip thickness
h^*_{cu}	[mm]	Specific chip thickness
$\overline{h_{cu}}$	[mm]	Approximated chip thickness
$\overline{h_{cu0}}$	[mm]	Approximated chip thickness of reference process
$h_{cu,max}$	[mm]	Maximum chip thickness
$h_{cu,m}$	[mm]	Mean chip thickness
$h_{cu,min}$	[mm]	Minimum chip thickness
h_d	[mm]	Dedendum height
h_R	[mm]	Height of tip relief
h_T	[mm]	Height of root relief
i	[-]	Transmission ratio
i_B	[-]	Current blade
i_G	[-]	Current blade group
i_R	[-]	Current cutterhead revolution
i_{SZ}	[-]	Number of cuts of KAMM model
i_ω	[-]	Current simulation increment
k	[mm³]	Kernel density acc. to LEBESGUE
k	[-]	Linear slope of TAYLOR and USUI model
$k_{1...10}$	[-]	Experimental coefficients
k_{Arc}	[-]	Proportionality factor of ARCHARD model
k_{dyn}	[N/mm²]	Specific cutting force
k_i	[-]	Bin interval
k_v	[-]	Linear slope of KAMM model

Symbol	Unit	Name
l	[mm]	Length of groove of RABINOWICZ
l	[m]	Tooth thickness of KÜHN model
l_{cu}	[mm]	Length of cutting arc
$l_{cu,cum,0}$	[m]	Cumulated length of cutting arc
$l_{cu,max}$	[mm]	Maximum length of cutting arc
$l_{cu,m}$	[mm]	Mean length of cutting arc
$l_{cu,min}$	[mm]	Minimum length of cutting arc
l_e	[mm]	Effective cutting length
$l_{e,cum}$	[mm]	Cumulated effective tool length
l_k	[m]	Contact length between flank face and workpiece
l_{norm}	[-]	Normalized tool life
l_s	[mm]	Unrolled profile edge
m	[-]	Experimental parameter of KAMM model
m	[-]	Slope of feed ramp
m	[-]	Thermal softening factor
$mccp$	[mm]	Machine center to crossing point
m_{nm}	[mm]	Normal mean module
n	[-]	Number of measurements
n	[-]	Number of teeth
n	[-]	Experimental parameter of KAMM model
n_{RMP}	[min^{-1}]	Rotational speed
$\vec{n}$	[mm]	Normal vector
n_{cu}	[-]	Number of cuts
n_{RP}	[-]	Number of rolling positions
p	[N/mm²]	Local pressure
r_1	[mm]	Coordinate of tool point in workpiece system
r_{12}	[mm]	Coordinate of tool point in cutterhead system
r_i	[mm]	Radius of tool point in cutterhead system
r_ε	[mm]	Corner radius
s	[mm]	Sliding distance of ARCHARD model

Symbol	Unit	Name
s	[-]	Standard deviation
s	[mm]	Unrolled profile edge
s^2	[-]	Variance
s_{mn}	[mm]	Chordal tooth thickness
s_{RF}	[mm]	Distance along rake face
t	[s]	Process time
t	[-]	Sample value
t	[-]	Value of t-test
t_c	[s]	Cutting time
t_g	[s]	Generating time
v	[m/s]	Cutting velocity of KAMM model
v_c	[m/min]	Cutting velocity
v_c^*	[-]	Specific cutting velocity
v_{eff}	[m/min]	Effective velocity
v_f	[m/min]	Feed velocity
v_{rel}	[mm/s]	Relative velocity of BINDER model
v_s	[m/min]	Sliding velocity
v_w	[°/s]	Rolling velocity
w_i	[%]	Mass fraction
x	[mm]	Sliding distance of RABINOWICZ model
x_i	[-]	Measurement i
$\tilde{x}$	[-]	Median
$\bar{x}$	[-]	Arithmetic mean
$x_{i,12}$	[mm]	x-coordinate of tool point i in cutterhead system
$y_{i,12}$	[mm]	y-coordinate of tool point i in cutterhead system
y_k	[-]	Observed value
$\bar{y}$	[-]	Arithmetic mean of observed data
$\tilde{y}_k$	[-]	Modeled value
z_0	[-]	Number of blade groups
z_2	[-]	Number of workpiece teeth

Symbol	**Unit**	**Name**
$z_{i,12}$	[mm]	z-coordinate of tool point i in cutterhead system
$\hat{z}$	[mm]	Final cutterhead position
A	[[-]	Experimental parameter of MUNDT model
A_{cu}	[mm²]	Machined area
A_{α}	[mm²]	Flank face
A_{Cr}	[µm²]	Area of tool cross section
A_{FF}	[µm²]	Area of flank wear
A_i	[div.]	Coefficients of GUTMANN model
A_{γ}	[mm²]	Rake face
B	[-]	Experimental parameter of MUNDT model
B	[-]	Tool life factor of HARDJOWSUWITO model
C	[-]	Experimental parameter of MUNDT model
$C_{1...17}$	[-]	Experimental parameters
C_v	[-]	Tool life at v_c = 1.0 m/min of TAYLOR model
CI	[-]	Confidence interval
E	[N/m²]	YOUNG's modulus
$F_{1...5}$	[-]	Experimental parameters of DAMMER model
F_C	[N]	Cutting force
F_D	[N]	Thrust force
F_D'	[N/mm]	Relative thrust force
F_N	[N]	Normal force
F_{tu}	[MPa]	Ultimate tensile stress
H	[HV]	Surface hardness of RABINOWICZ model
H_0	[HV]	Tool hardness at reference temperature
H_a	[kg/mm²]	Hardness of abrasive body
H_b	[kg/mm²]	Hardness of basic body
H_d	[HR]	Tool hardness
H_h	[HV]	Hardness of hard body
H_i	[-]	Absolute frequency
H_{max}	[HB]	Maximum blank hardness

Symbol	Unit	Name
H_{min}	[HB]	Minimum blank hardness
H_s	[HV]	Hardness of soft body
H_{St}	[-]	Multi-flank factor
IQR	[-]	Inter quartile range
K	[-]	Tool geometry factor
K_1	[-]	Experimental parameter of CERETTI model
K_G	[-]	Wear characteristic of HARDJOSUWITO model
K_v	[J]	Wear characteristic of KÜHN model
KB	[mm]	Crater width
KF	[mm]	Crater front distance
KM	[mm]	Crater center distance
KT	[mm]	Crater depth
L	[m]	Tool life
L_0	[m]	Tool life of reference process
$L_{S,flank}$	[m]	Tool life for flank wear
$L_{S,crater}$	[m]	Tool life for crater wear
L_v	[-]	Dominating wear mechanism
N	[-]	Number of cut parts
N_{EF}	[-]	Tool life for single-flank cut
N_{MF}	[-]	Tool life for multi-flank cut
P_{ne}	[mm²]	Cutting edge normal plane
P_{re}	[mm²]	Working reference plane
P_{se}	[mm²]	Working cutting edge plane
Q	[kJ/mol]	Activation energy
Q_1	[-]	First quartile
Q_3	[-]	Third quartile
$Q_{p=\alpha\%}$	[-]	α-quantile
R	[J/K·mol]	Universal gas constant
R^2	[-]	Coefficient of determination
R_b	[-]	Ratio of chip width

Symbol	Unit	Name
R_{fl}	[mm]	Reference cutter radius
R_h	[-]	Ratio of chip thickness
R_{hb}	[mm]	Radius of curvature
R_w	[mm]	Nominal cutter radius
Ra	[µm]	Arithmetic mean roughness
Rz	[µm]	Average surface depth
SE	[-]	Standard error
ST	[mm]	Feed per blade group for feed ramps
$ST_{1...4}$	[mm]	Data point for feed of feed ramp
S_α	[mm]	Distance on flank face
S_γ	[mm]	Distance on rake face
T	[K]	Temperature
T_0	[K]	Reference temperature
T_c	[min]	Tool life
T_m	[K]	Melting temperature
TA	[mm]	Plunging depth
$TA_{1...4}$	[mm]	Data point for plunging depth of feed ramp
TA_e	[mm]	Total plunging depth
U	[-]	Engagement ratio
V	[-]	Variation coefficient
V	[mm³]	Wear volume
V_{cu}	[mm³]	Chip volume
V_h	[mm³]	Wear volume of hard body of RABINOWICZ model
V_a	[µm³]	Approximated wear volume
V_s	[mm³]	Wear volume of soft body of RABINOWICZ model
VB	[mm]	Width of flank wear
VB_C	[µm]	Width of flank wear on profile radius
$VB_{norm,0}$	[µm]	Normalized obtained flank wear
VB_i	[µm]	Individual width of flank wear
VB_{max}	[µm]	Maximum width of flank wear

Symbol	Unit	Name
VB_m	[µm]	Mean width of flank wear
W	[mm³]	Tool wear
W_{abr}	[mm³]	Abrasive tool wear
$W_{p/c}$	[mm³]	Physical / chemical tool wear
$\overline{X}$	[-]	Arithmetic average of test
$\overline{Y}$	[-]	Arithmetic average of reference
Z_{AB}	[mm]	Abrasive wear depth

Greek

Griechisch

Symbol	Unit	Name
α	[°]	Cradle angle
α	[-]	Level of significance
α	[°]	Relief angle
α_1	[°]	Beginning of cradle interval
α_2	[°]	End of cradle interval
α_d	[°]	Designed relief angle
α_m	[°]	Mean cradle angle
α_{ne}	[°]	Effective relief angle
α_P	[°]	Profile angle
α_R	[°]	Root relief angle
α_T	[°]	Tip relief angle
α_w	[°]	Effective relief angle of KÜHN model
β	[°]	Wedge angle
β	[°]	Workpiece rotational angle
γ	[°]	Machine root angle
γ	[°]	Rake angle
γ_d	[°]	Designed rake angle
γ_{ne}	[°]	Effective rake angle
γ_s	[°]	Rake angle in tool plane
$\delta_{1/2}$	[-]	Limits of equivalence interval