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Microstructuring of Thermo-Mechanically Highly Stressed Surfaces

Final Report of the DFG Research Group 576

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Preamble

The fuel consumption of a modern combustion engine is one of the most important purchase criteria in contemporary society. Increasing oil prices and exhaust emissions taxes force the automotive industry to continuously improve the vehicle engines. The fuel consumption is closely related to the frictional losses of an engine. New material pairings or constructive modifications of the piston group can reduce such losses. Another innovative concept to lower the frictional forces is the micro-structuring of thermo-mechanically highly stressed surfaces. Within an interdisciplinary research group sponsored by the German Research Foundation, scientists at the Leibniz Universität Hannover and Universität Kassel have been working together to investigate this research topic. This final report presents their findings and offers scope for further discussion.

On behalf of the DFG research group 576,

Hannover, 1st of October, 2013

B. Denkena

(spokesman of the DFG research group 576)

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Formula symbols and abbreviations

Formula Symbols

Sign	Unit	Description
Δa_p	μm	depth of cut deviation
A	μm^2	cross section projection area
A_c	mm^2	cross-section of undeformed chip
A_E	μm^2	longitudinal section projection area
A_{MT}	mm^2	micro-dimple area
A_p	μm^2	plane projection area
a_p	μm	depth of cut
$a_{p,fit}$	μm	cut depth by circular fit
$A_{p,hist}$	-	threshold dimple depth
$a_{p,max}$	μm	maximum depth of cut
$A_{tot.}$	mm^2	total surface area
A_V	1	area of all pores divided by measured area
A_{WZ}	Mm^2	cross section tool
b	μm	length of cross section / micro-dimple width
b	mm	bore
$b_{a,d(,hist)}$	μm	width of ridges on side d(left, right) (histogram based)
b_{WZ}	mm	cutting tool width
D	mm	component diameter
D	-	damping matrix
$d(x,y)$	μm	Euclidian metric
D_{MT}	-	number of dimples for a rectangular elemental surface
f_0	Hz	natural frequency
$F_{a,tool}$	mm	axial feed rate
f_{ab}	-	relative cut volume
$F_{accurate,interp}$	μm	polynomial surface fit of $M_{2,interp}$
$F_{accurate,zero}$	μm	polynomial surface fit of $M_{2,zero}$
f_{ax}	mm	axial feed rate

F_{basic}	μm	basic polynomial surface fit
F_{c}	N	cutting force
f_{err}	Hz	excitation frequency
F_{i}	N	outer forces
F_{n}	N	normal force
F_{p}	N	passive force
F_{r}	N	friction force
G_{u}	-	upsetting rate
G_{s}	-	stretching rate
$h_{\text{a,l,hist}}$	μm	height of ridges on side d(left, right) (histogram based)
$\bar{h}$	μm	gap
K	-	stiffness matrix
k_{c}	N/mm^2	specific cutting force
k_{p}	N/mm^2	specific passive force
l_{E}	μm	length of cut by circular fit
l_{g}	mm	contact length
l_{s}	μm	length of longitudinal section / micro-dimple length
M	μm	measured surface data
m	g	mass
M	-	mass matrix
M_1	μm	basic form correction of surface M
$M_{2,\text{interp}}$	μm	M_1 with interpolated structure regions
$M_{2,\text{zero}}$	μm	M_1 with zeroed structure regions
$M_{3,\text{interp}}$	μm	form correction of $M_{2,\text{interp}}$
$M_{3,\text{zero}}$	μm	form correction of $M_{2,\text{zero}}$
$M_{4,\text{interp}}$	μm	final correction of surface M by interpolated structures
$M_{4,\text{zero}}$	μm	final correction of surface M by zeroed structures
M_{Fr}	Nm	friction torque
n	1/min	revolutions per minute
n_{comp}	min^{-1}	component revolution speed
n_{max}	min^{-1}	maximum revolution speed

n_{tool}	min^{-1}	tool revolution speed
p	Pa	pressure
p_{atm}	bar	atmospheric pressure
p_{cyl}	bar	cylinder pressure
p_{max}	bar	maximum cylinder pressure
p_n	bar	indicated pressure
$p_{\text{structure}}$	μm	height data of the bounding box of one micro cut
$\bar{p}$	Pa	average pressure in the lubricant film
R_a	μm	arithmetical deviation of the roughness profile
$R_{a,l}$	μm	mean longitudinal roughness
$R_{a,q}$	μm	mean cross roughness
r_i	mm	component inner diameter
R_{max}	μm	maximum roughness depth
R_{NaN}	-	R_{zero} (1 replaced by NaN)
R_{ridge}	-	ridge mask
r_{rot}	mm	rotational diameter
$R_{\text{structures}}$	-	structure mask
r_{tool}	mm	tool radius
r_{WZ}	mm	tool radius
R_z	μm	average surface roughness
R_{zero}	-	structure mask, calculated for M_1
r_β	μm	cutting edge radius
r_ϵ	μm	edge radius
s	mm	stroke
s_{ax}	mm	axial micro-dimple distance
S_{MT}	%	micro-dimple ratio
spf_X	-	quotient of parameter X for structure and tool
s_{rad}	mm	radial micro-dimple distance
s_{tan}	mm	tangential micro-dimple distance
$s_{v,\text{dyn}}$	μm	dynamic tool displacement
$s_{v,\text{min}}$	μm	minimum tool displacement

$\vec{s}_c$	μm	cross section
$\vec{s}_i$	μm	longitudinal section
$\vec{s}_{\text{tool}}$	μm	longitudinal section of cutting tool
t	s	cutting time
T_e	Nm	torque at the engines output
t_{ridge}	μm	threshold value for ridge identification
$t_{\text{structure}}$	μm	threshold value for micro cut identification
t_{tan}	°	tangential indexing
U_{BT}	mm	component's circumference
u_i	m/s	surface velocity
V	μm^3	structure volume
v	m/s	sliding speed
V_{burr}	μm^3	modelled burr volume
v_c	m/min	cutting speed
v_{comp}	m/min	component speed
V_G	μm^3	burr volume
V_H	cm ³	displacement
V_{MT}	μm^3	micro-dimple volume
v_{tool}	m/min	tool speed
V_v	%	pore volume percentage
$V_{v,\text{sp}}$	-	specific volume
w	μm	width of machined microstructures
x	Mm	Global deformation
x_i	mm	(film) coordinates
$x_{\text{scale}}, y_{\text{scale}}$	μm	resolution along x-/y-axis
$xy_{\text{scale}}(\phi)$	μm	mean resolution along an axis with angle ϕ to the x-axis

Symbols

Sign	Unit	Description
γ	°	angle of cut
ϕ	°	polar coordinate

$\Delta\mu$	-	friction coefficient deviation
σ	-	standard deviation
φ	°	alignment angle
φ_{tan}	°	parallel offset between two micro-dimples
2Θ	°	diffraction angle
α	°	clearance angle
α_{crit}	°	critical clearance angle
α_{eff}	°	effective clearance angle
ε	°	edge angle
ϕ	°	shear angle
γ	°	rake angle
γ_{eff}	°	effective rake angle
κ	°	flank angle
κ_{eff}	°	effective tool cutting edge angle
λ	-	chip compression ratio
λ_{limit}	-	revolution ratio limit
λ_n	-	revolution ratio
λ_s	°	tool cutting edge inclination
λ_v	-	speed ratio
μ	-	friction coefficient
μ_F	-	force ratio
μ_{min}	-	minimum friction coefficient
Φ^p	-	pressure flow tensor
Φ^s	-	shear flow tensor
η	m^2s^{-1}	dynamic viscosity

Abbreviations

Sign	Description
Al_2O_3	white alumina
AlSi17Cu4Mg	hypereutectic aluminum-silicon-alloy
APS	atmospheric plasma spray

BMEP	break mean effective pressure
BSE	back scattered electron
CCD	chip white light interferometer
CO ₂	carbon dioxide
CVD	chemical vapour deposition
EPMA	electron microprobe analyzer
Fe50Mo	iron and molybdenum mixture
FeCr13	chromium-based steel
FeCr13/Mo	chromium-based steel and molybdenum mixture
FeMo	iron and molybdenum mixture
FMEP	friction mean effective pressure
GJS400	spherulitic graphite cast iron
HV	Vickers hardness
IMEP	indicated mean effective pressure
Mo/NiCrBSi	molybdenum and nickel alloy mixture
NA	numerical aperture
NLPM	normal liters per minute
RRV	rotational friction wear tests
RT	room temperature
S235JR	steel
SEM	scanning electron microscope
WLI	white light interferometer
XRD	X-ray diffraction