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DRY CONSTANT-LOAD STEEL ALUMINA GRINDING ENERGY PARTITION

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Abstract

The paper deals with the new, original model of energy partition in dry constant-load steel grinding. Experimental setup, experiment conditions and analyses were shown and discussed in this article. New findings are presented for energy flux distribution and energy partition ratios. Energy partition ratios, determined during experiments were compared with theoretical values for constant, maximum energy carried away by the grinding chips e_{cc}*, approximately 6 J/mm*^{3}*. Original model, based on grinding chips stream temperature measurements was used for chips energy partition ratio* R_c *evaluation. Measurements were made using high-class testing equipment, e.g. Kistler 9257B dynamometer and Minolta-Land Cyclops optical pyrometer. A case study based on constant-load grinding C45 (AISI 1045) with alumina grinding wheels is used to illustrate the variability of energy carried away by the grinding chips. Developed model of grinding energy partition can be useful for on-line grinding control systems, especially for low specific grinding energy and high efficiency grinding processes.*

Keywords: g*rinding, alumina, dry machining, energy, modeling*

1. Introduction

Grinding requires higher specific energy than other conventional machining processes like milling, shaping, turning, etc. There is a long history of calculation of grinding energy partition ratios and temperatures of workpiece, grinding wheel, coolant, grinding chips and environment. Most important key findings in the development of grinding processes thermal modeling [2,5,6,7,9,10,11,12,13,14,17] are listed in Tab. 1.

Tab. 1. Chosen key findings in the development of grinding processes thermal modeling

Author, year of publ.	Model description
Jaeger (1942)	Sliding (moving) heat source
Outwater (1952)	Shear plane partition model
Hahn (1962)	Partition between workpiece and grain
Makino (1966)	Real contact length l_e tool with workpiece grater than geometrical contact length l_g
Des Russeaux (1970)	Fluid convection model
Malkin (1971/1974)	Limiting chip energy; $e_{cc} \cong 6$ J/mm^3, energy partition models

Shafto (1975)	Coolant film boiling, coolant energy limitation
Snoyes (1978)	Triangular heat flux distribution
Werner (1980)	Energy flux to: wheel-workpiece-coolant-chips
Howes (1987)	Fluid film boiling (in contact zone)
Pettit (1988)	Energy partition between wheel and workpiece
Lavine (1989)	Conical (one dimensional) grain model
Rowe (1991)	Transient contact (heat transfer) model
Qi (1993)	Contact lenhgt based on contact forces
Rowe (1993)	Force/contact length model
Ueda (1993)	Active grains temperature
Rowe (1994/95)	Critical temperature (of thermal damage)
Tönshoff (1995)	Critical temperature for tensile
Rowe (1996)	Effective grain thermal properties
Rowe (2001)	Inclined heat source model – conditions of e_c value reduction

Most analyses were made for constant, maximum specific energy carried away by the grinding chips e_{cc}=const≅6 J/mm^3. Rowe suggested [12] lower maximum chip energy for cast iron at 1500^{o}C; approx. 5,28 J/mm^3. Tso et al. [18] determined minimum specific chips energy e_{cc}≅2 J/mm^3. Chips specific energy also as chip energy partition coefficient R_{chips} is important component of total grinding energy partition flux distribution, especially when grinding at low specific energies. Examples of workpiece energy partition coefficient, as other way of total energy partition, R_w values, determined by researchers was shown in Tab. 2.

Tab. 2. Examples of workpiece energy partition R_w values

Author, year of publ.	R_w values	Grinding conditions
Rowe, Pettit (1988) [14]	~ 52÷75 %	dry, for v_w 0,1÷0,9 m/s
Rowe (1995) [10]	~ 75% for Al_2O_3	a_e 0÷14 µm, v_c=30 m/s, v_w=0,3 m/s, CCS
Shaw (1994, 1996) [15]	~ 80% for Al_2O_3 or SiC ~ 50% for Al_2O_3 or SiC ~ 5% for Al_2O_3 or SiC	Dry form and finish grinding (FFG) FFG with coolant v.coarse, dry stock removal grinding (SRG)
Chang, Szeri (1997) [1]	~ 5% for Al_2O_3 ~ 30% for Al_2O_3	creep-feed, water, v_c=18 m/s, v_w=1,2 mm/s, a_e=0,5 mm creep-feed, oil, v_c=18 m/s, v_w=1,2 mm/s, a_e=0,5 mm
Wang, Fuh (1998) [19]	~ 25% for Al_2O_3, when $(v_s/v_w)^{0,5}$>100	creep-feed, steel, oil, v_c=18 m/s, a_e=1 mm
Rowe (2001) [3]	~ 5÷75 %, Al_2O_3	Deep grinding, v_c=55 m/s, a_e 0,4÷1 mm, v_w 0,2÷0,3 m/s
Jin, Stephenson (2003) [4]	~ 5÷35 %, CBN	HEDG, steel, v_c=150 m/s, a_e=3 mm, oil, Q'_w 0÷1000 mm^3/mm s

2. Experimental

Experimental, original set up is illustrated schematically in Fig. 1.
Main testing equipment were:

- Kistler dynamometer 9257B connected with amplifier 5017 for grinding force components measurements,
- Cyclops 152A Minolta-Land pyrometer for grinding chips temperature measurements,
- Metex M-3860M multimeter for power consumption measurements.

Equipment listed above and other instrumentation were connected with AD/DA PCI1710 card (through connecting interface PCLD-8710) for signals values acquisition and grinding system control. Original software was made.

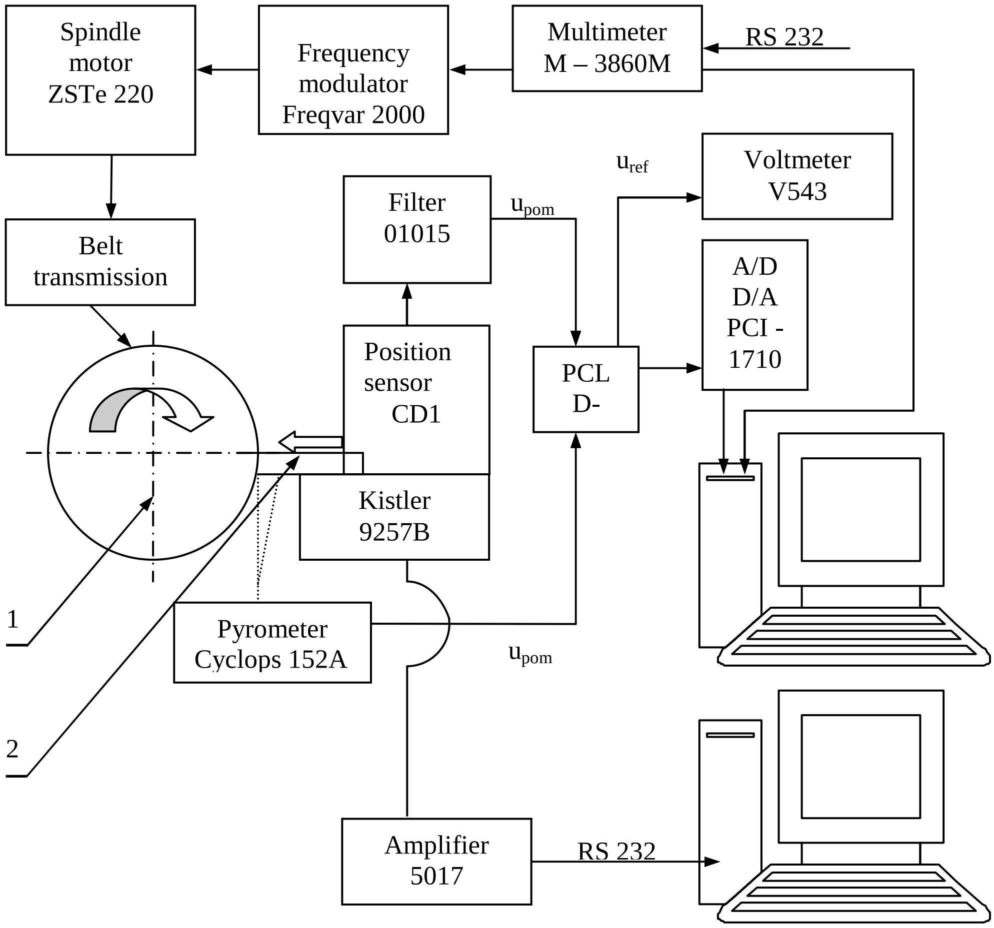

Fig. 1. Experimental set up schematic diagram; 1 – grinding wheel, 2 – workpiece

Experimental conditions:

- grinding wheels characteristics: 1-250x25x76 99A, 24 or 46 or 60, V or B or B10, example of full characteristic; 1-250x25x76 99A 24 M5 B10 50,
- grinding speed v_c: (12, 25 and 38) m/s,
- quasi constant-load force: (34,4 or 51 or 57,7) N as force used for workpiece-to-grinding wheel clamp,
- workpiece material: plain carbon steel C45 (AISI 1045), section dimensions: 10 x 10 mm,
- dry grinding.

Measured values: grinding force components, grinding sparks stream temperature, workpiece linear wear (for workpiece speed v_w evaluation), power consumption.

3. Results and analysis

Specific grinding energy can be determined from active grinding power consumption or tangential grinding force component:

$$e_c = \frac{F_t \cdot v_c}{Q_w^{'}} = \frac{P_{sc}^{'}}{Q_w^{'}} \quad [\mathrm{J/mm^3}], \tag{1}$$

where:

- $F_t \cdot v_c = P_{sc}^{'}$ – specific active grinding power; F_t – tangential grinding force component,
- $v_w \cdot b \cdot a_e = Q_w^{'}$ – specific volumetric removal rate.

Chips energy partition coefficient R_{chips} is a part of grinding chips specific energy e_{cc}=6 J/mm^3 in total specific grinding specific energy e_c:

$$e_{cc} = R_{chips} \cdot e_c \quad [\mathrm{J/mm^3}]. \tag{2}$$

There is no possibility for measure grinding chips („made” from workpiece material), grinding wheel grains and bond temperatures in contact area without invasion in workpiece-grinding wheel set-up. Thus temperature of grinding spark stream as calorimetric measurement was made for grinding sparks specific energy evaluate. The total grinding spark stream energy can be calculated from :

$$E_{tot} = E_{kin} + E_{ter} \quad [\mathrm{J}], \tag{3}$$

where:

- E_{tot} – total grinding spark stream energy,
- E_{kin} – total spark stream particles kinetic energy,
- E_{ter} – total spark stream particles thermal energy.

$$E_{tot} = \frac{m_{parts} \cdot v_c^2}{2} + R_{chips} \cdot e_c \cdot v_w \cdot a_e \cdot b \cdot t_c \quad [\mathrm{J}], \tag{4}$$

$$m_{parts} = \rho_{temp} \cdot v_w \cdot a_e \cdot b \cdot t_c \quad [\mathrm{g}], \tag{5}$$

where:

- ρ_{temp} – transient workpiece material density in g·mm^{-3}, calculated in spec. temperature [8],
- v_w – workpiece linear speed in mm/min,
- a_e – grinding depth in mm,
- b – active grinding width in mm,
- t_c – contact time in min,
- m_{parts} –workpiece removed mass in g.
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Grinding chips specific energy e_{cc} (based on thermal material properties):

$$e_{cc} = \rho_{temp} \cdot c_{p\_temp} \cdot \Delta T \quad [\mathrm{J/mm^3}], \tag{6}$$

where:

- ΔT – measured chips (spark stream) temperature increase (from normal environment temperature),
- c_{p_temp} – transient workpiece material specific heat in J/kgK [8].

After transfiguration total E_{tot} can be found from:

$$E_{tot} = \rho_{temp} \cdot v_w \cdot t_k \cdot b \cdot a_e \cdot (\frac{v_c^2}{2} + c_{p\_temp} \cdot \Delta T) \text{ [J]}, \quad (7)$$

and total chips energy partition coefficient R_{chips}:

$$R_{chips} = \frac{[\rho_{temp} \cdot (\frac{v_c^2}{2} + c_{p\_temp} \cdot \Delta T)] \cdot v_w \cdot b \cdot a_e}{v_c \cdot F_T} \quad (8)$$

Values of chips energy partition coefficient R_{chips} determined for: theoretically constant grinding chips specific energy $e_{cc} \cong 6$ J/mm^3 and differential values of e_{cc} calculated with spark stream temperature and tangential grinding force are illustrated in Fig. 2. Statistic based models and parameters are presented in Fig. 2.

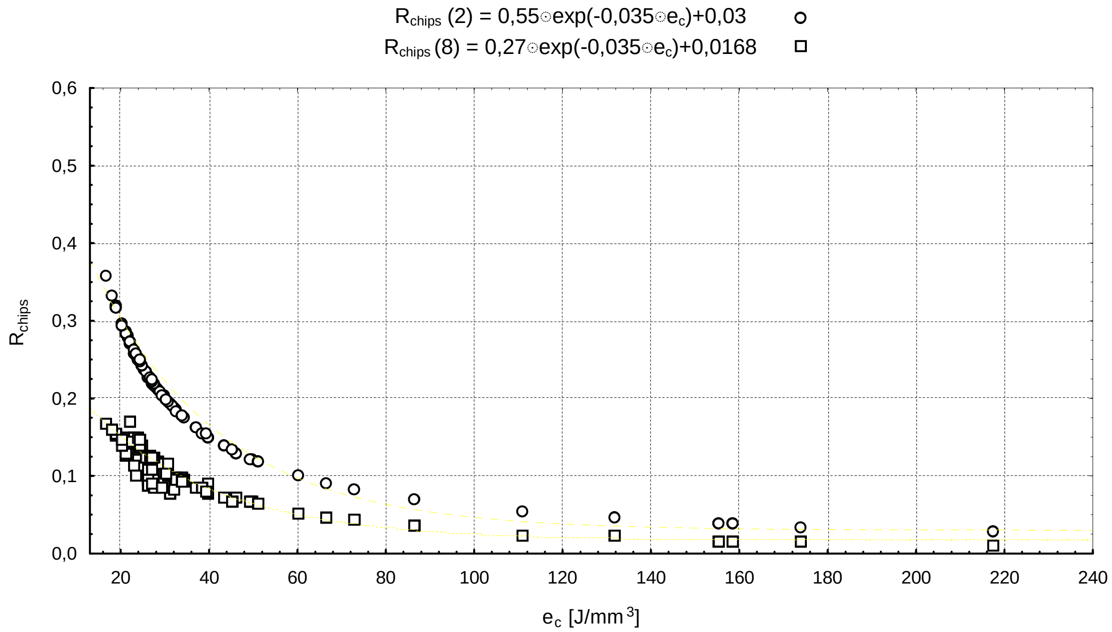

Fig. 2. Chips energy partition coefficient R_{chips} values for different specififc grinding energy:
- *for e_{cc} = const = 6 J/mm3, determined from eq. (1) and (2)- upper line; statistical parameters: e_c: R_{chips}: R = -0,806, α = 0,00; y = 0,267 - 0,0016·e_c,*
- *for e_{cc} determined from eq.(8), based on thermal spark stream measurements – lower line; statistical parameters: e_c: R_{chips}: R = -0,797, α = 0,00; y = 0,135 - 0,00082·e_c.*

Analyzing Fig. 2. one very important finding can be made; a part of grinding energy is not fully dissipated to grinding chips as follows from previous theoretical analysis. Depending on specific grinding energy difference can exceed 50% for low specific grinding energy techniques. A apart of grinding energy, previously calculated as distributed to chips can be dissipated to other places; workpiece, wheel or environment.

4. Conclusions

- Grinding energy dissipated to grinding spark stream was reaching differential values; lower than theoretically constant grinding chip formation specific energy $e_{cc} \cong 6$ J/mm^3.
- Chips energy partition coefficient R_{chips}, determined for differential values of e_{cc} calculated with spark stream temperature and tangential grinding force had always lower values than coefficient R_{chips} calculated in the same experiment point for theoretical chip formation specific energy.

- Developed model, based on spark stream temperature, tangential grinding force or power consumption measurements and workpiece thermal properties, can be useful for on-line grinding control systems. The best application for described model should be systems dedicated for low specific grinding energy processes.

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