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Cut-off grinding of hardened steel wires - modelling of heat distribution

Matthias Putz[a], Macario Cardone[a,*], Martin Dix[a]

[a] *Institute for Machine Tools and Production Processes, Chemnitz University of Technology, Chemnitz, Germany*

* Corresponding author. Tel.: +49-(0)371-531-33635; fax: +49-(0)371-531-832631. *E-mail address:* macario.cardone@mb.tu-chemnitz.de

Abstract

Cut-off grinding is an applied machining technology to separate high strength steel bars. Due to the high heat generation and geometrical boundary conditions, diverse thermally induced defects occur in the machined part, for example grinding burn and burr formation. Based on FE analysis, the heat distribution inside the steel bar was calculated for different cutting conditions with the goal of minimizing these manufacturing errors. The critical maximum workpiece temperature decreases up to forty-eight percent by adapting the cutting parameters and cooling strategy. The numerical model and calculated temperature distributions were verified via experimental analysis.

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Keywords: Grinding; High strength steel; Finite element method (FEM)

1. Introduction

Cut-off grinding is a machining process with the goal of separating high strength material bars of various shapes, such as tubes, wires and rail tracks [1]. This cutting operation takes place by means of an abrasive grinding wheel with an outer diameter up to 500 mm, whose thickness lies between 1 and 5 mm [2].

Among the many industrial applications of cut-off grinding, this paper focuses on the machining of high-strength steel wire races for ball bearings. These steel strands need to be separated, before being mounted into the bearing so that they can properly guide the rolling spheres. Unfortunately, the machined wire races exhibit some of the typical thermally induced defects of conventional grinding processes, for instance burr formation, workpiece burn and residual stresses [3]. These machining errors can effectively be avoided or reduced by implementing low-temperature grinding operations [4].

This work presents an FE-based analysis of the most important kinematic, geometrical and cooling parameters, which characterize the cut-off grinding of high-strength steel wires. The aim of this systematic investigation is to adjust the machining parameters in order to significantly reduce the workpiece temperature during the cutting process. The results deriving from the FE-Simulations have been experimentally validated.

2. Experimental

A dedicated test bench has been designed and assembled on a high-speed cutting center with the aim of reproducing the machining condition of industrially applied cut-off grinding processes (Fig. 1).

A high-strength steel strand is fixed by means of two pairs of clamping devices, with a gap of 8 mm between each other, so that an appropriate grinding wheel can separate the wire. The strand material is an oil hardened and tempered alloy steel 1.7102, while the grinding tool is a 20A70/5JB7-50 aluminum oxide abrasive wheel with 150 mm radius and 2 mm thickness. The wire diameter ($ø_w$) varies from 4 up to 12 mm. Two 1 mm diameter holes have been drilled within the tested strands so that a pair of type K metal sheathed thermocouples could be inserted in them, with the aim of measuring the workpiece temperature during the grinding process (T_{tc}). These holes are as deep as the half of the wire

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diameter and have a distance of 8 mm from each other, so that the grinding wheel can separate the steel wire while keeping the same constant distance of 3 mm from both thermocouples. An infrared thermometer has also been integrated within the test facility, with the aim of measuring the wire surface temperature in the cut-out zone (T_p). The implemented pyrometer is characterized by a spectral sensibility of 2.3 µm and a measuring range between 150°C and 1000 °C. In order to effectively investigate the volume reduction of the grinding wheel, a steel sphere linear position sensor has been added to the test machine. By means of this device, the grinding wheel diameter can be measured before and after each machining process. Finally, a pair of coolant nozzles is available, with the goal of providing the cutting fluid (water based emulsion with 5% oil concentration) to the cutting zone.

With the help of the servo trace function available on the CNC machining center, it is possible to quantify the grinding power (P_s) during the cutting process.

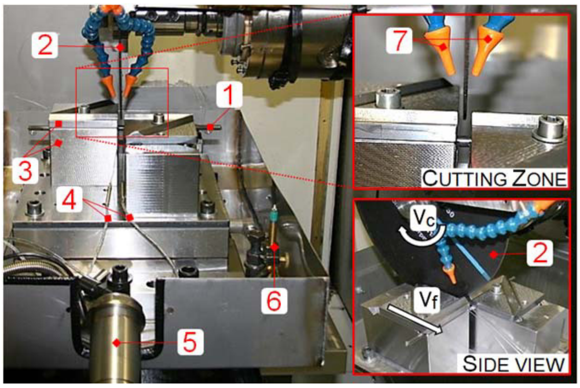

Fig. 1. Test bench: (1) steel wire; (2) grinding wheel; (3) clamping devices; (4) thermocouples; (5) pyrometer; (6) linear position sensor; (7) coolant nozzles.

Figure 2 shows the most important parameters which can be investigated by means of the presented test facility. An initial state has been defined for the cut-off grinding process on the basis of industrially used data as follows: $v_c = 40$ m/s; $v_f = 256$ mm/min; k = 1; ω = 90°; $\dot{V}_{CL} = 5.2$ l/min.

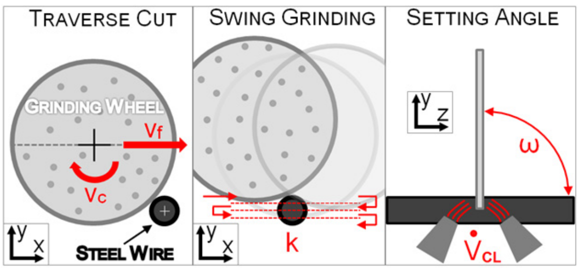

Fig. 2. Investigated process parameters: cutting speed (v_c); feed rate (v_f); number of swings (k); setting angle (ω); coolant volume flow rate ($\dot{V}_{CL}$).

According to the initial state, the proposed grinding strategy is a conventional traverse cut. The wheel, whose radius is 150 mm, has a linear movement parallel to the x-axis, while keeping a constant y-distance of 144 mm from the wire axis, so that the strand separation takes place through one grinding pass (k = 1). An alternative cutting strategy involves the so-called swing grinding, which consists of several traverse cuts (k > 1) as a result of a pendulum movement of the grinding wheel [5]. All the experimental tests have been realized in down grinding.

3. Finite element analysis

A dedicated 3D thermal FE-model has been developed for the investigated process with the help of the software MSC.MARC®. The aim of the numerical analysis is to characterize the heat distribution within the workpiece during the grinding process. The steel wire has been modelled as a 3D mesh consisting of several pentahedral elements, whose average size is 0.3 mm. The parameters used for the workpiece material are available in Table 1.

Table 1. Material parameters for alloy steel 1.7102 [6, among others].

Temperature [°C]	23	100	200	300	500	700
Thermal conductivity [W/m·K]	42.6	42.2	40	37	31.4	26.2
Specific heat [J/g·K]	0.47	0.49	0.53	0.56	0.66	0.77
Density [g/cm³]	← 7.85 (constant) →					

The thermal load deriving from the grinding operation has been modeled as a surface heat flux as follows [7]:

$$Q_w = h_m \cdot \frac{P_s}{b_s \cdot l_g} \quad (1)$$

The calculated Q_w is characterized by a constant, uniformly distributed heat flux density and moves through the workpiece with the same feed rate of the grinding wheel in the real machining operation. The heat distribution factor h_m defines the portion of thermal energy generated during the grinding process that is absorbed by the workpiece [7]. On the basis of the experimentations conducted in dry conditions, the non-dimensional value of this coefficient has been set as $h_m = 0.45$. P_s represents the grinding power, while b_s and l_g respectively define the width and the length of the contact between wheel and wire.

The selection of a uniform heat flux distribution is strictly related to the geometrical intersection between wheel and steel wire during the machining process, which results in a ring-shaped geometry with an approximatively constant thickness. This is a remarkable difference with the conventional surface grinding, according to which the intersection between tool and workpiece generates a typical comma-shaped geometry with a variable thickness. As a consequence, a triangular heat flux distribution is recommended when modelling the heat generated into the workpiece for surface grinding operations but doesn't represent the most appropriate choice for cut-off grinding processes.

Since the average value of the ratio between l_g and the residual wire volume to be machined is nearly constant for all the analysed workpieces, it is appropriate to set h_m as a