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Evolution of surface roughness in grinding and its relationship with the dressing parameters and the radial wear

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Abstract

Grinding is a machining process specially indicated for finishing operations in hard materials, in order to obtain low surface roughness (Ra 0.1µm to 2µm) and tight tolerances. The cutting tool is the grinding wheel which is formed by abrasive particles attached in a bond. The wear of these abrasive particles modifies significantly the roughness obtained in the workpiece. In this work, the evolution of part roughness has been continuously monitored as the grinding process progresses and the wheel gets worn. The roughness evolution is then related to different process variables such as the dressing parameters, the grinding conditions, the grinding forces and the radial wear of the wheel.

Keywords: Grinding; Surface Roughness; Evolution; Dressing

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1. Introduction

The grinding process is used as finishing operation due to its capacity to obtain high quality parts. Surface roughness is one of the most important quality attributes to be obtained on the ground part by Xiao and Malkin (1996). The grinding wheel, the tool of this process, should be selected carefully to suit the application for which it

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is required by Malkin (2008). In previous works, a methodology to analyze and compare the performance of different grinding wheels for the same application was developed by Fernandez et al. (2011).An extension of this research is presented in this paper focusing in the surface roughness. The importance of the dressing conditions to obtain good roughness in the workpiece is discussed.

The evolution of the surface roughness has been studied from the very moment the abrasive wheel is freshly dressed until it stabilizes. A close relationship between the measured roughness and the radial wear of the wheel has been found.

In the grinding process the roughness highly depends on the wear level of the abrasive grains. The life-cycle of these grains starts right after they are dressed with one or several diamonds (dressing tool). Three kinds of dressers can be distinguished: single-point diamond, multipoint diamond and multipoint diamond (cluster). The first is used to obtain special profiles in the wheel, i.e. grinding thread. The other two types of dressing tools are in general used to provide the wheel with a perfect cylinder-like shape for grinding flat surfaces, i.e. slide ways. Apart from the dressing tool, the cross feed velocity and depth of cut during dressing play a major role on the obtained generated wheel surface topography by Xiao and Malkin (1996). This generated topography (including grain size) along with the process parameters generates the final roughness on the workpiece. Then, this roughness evolves as the grinding process progresses and the abrasive grains wear out.

Three different micro-wear mechanisms can be distinguished in abrasive grains: attrition, grain fracture and bond fracture. The attritious wear happens when the tip of the grain is broken slightly. Further development of the attritious wear leads to flat grains tips (so called wear flat area). If the grinding force is increased, the grain is fractured and a significant part of the grain is lost while a new cutting edge is created. The last wear mechanism is bond fracture and leads to breakouts of entire grains by Badger (2010) (see Fig. 1).

In general, the evolution of wheel wear and generated workpiece roughness depend on the combination of three factors: the wheel, the dressing process and the grinding process. Even if the grinding wheel and the grinding process are kept constant, roughness can end up evolving in three different ways depending on the applied dressing. A "soft" dressing produces a low initial roughness that tends to increase towards a steady-state roughness value as wheel wear progresses because the grains break and create sharper edges than the slightly flat grain-tips created during dressing. In the opposite side, an "aggressive" dressing produces a high initial roughness that decreases as the wheel is used due to the proliferation of wear flat areas on the tips of the grains as opposed to the rough initial topography created during dressing. The third way is when some sort of equilibrium is found and the dressing tool produces a wheel topography similar to that of a used grinding wheel by Xiao and Malkin (1996).

The aim of this paper is to find the explanation behind the different ways in which workpiece surface roughness can evolve, depending on the applied dressing. The implication in this phenomenon of grinding force and radial wear (apart from grain wear) is also discussed.

2. Methodology and Experimental Procedure

A series of tests were carried out including 8 dressing conditions and 2 different process conditions (soft and aggressive conditions). The 8 dressing conditions included 2 depths of cut a_d (0.01 mm and 0.02 mm) and 4 cross feed speeds s_d (50 mm/min, 100 mm/min, 200 mm/min and 300mm/min). Grinding process conditions were divided into "soft" (v_w = 10,000 mm/min and a_e = 0.01 mm) and "aggressive" (v_w = 20,000 mm/min and a_e =0.02 mm). In order to reduce testing time and speed wheel wear both grinding conditions (soft and aggressive) are slightly biased towards the rough side. 2 tests per configuration were carried out to reduce stochasticity of results.

2.1. Equipment

The equipment used during the tests were:

- T500 HOMMEL-ETAMIC GmbH (Roughness Tester)
- Kistler 9257B (Multi Component dynamometer)
- Laser KEYENCE LK-G30 CCD (Laser Displacement Sensor)
- A grinding wheel 5MBA-46-G12-V489-P24P

- Workpiece material was an F-5229 steel Part with a dimension of 150X60X10 mm.

2.2. Methodology

The methodology to measure the different variables of the grinding process is explained in the next lines.

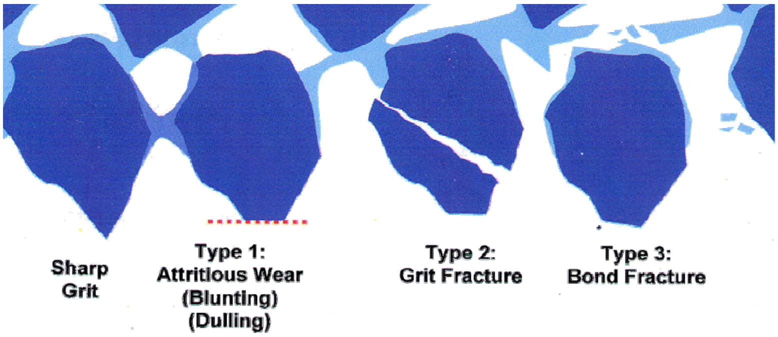


Fig. 1. Micro-wear mechanisms in abrasive grains: sharp grit, attritious wear, grit fracture and bond fracture [4].

- Roughness: in each test, roughness was measured six times (in order to avoid measurement stochasticity) at intervals after several volume of material was removed from the workpiece (15, 30, 45, 90, 180, 270, 360, 450, 600 and 750 mm^3/mm). The right position of the roughness tester was regulated by a column. The set-up is shown in Fig. 2 (a).
- Radial wear: radial wear was measured at the end of each test. The measuring procedure consisted copying the profile of the grinding wheel on a 1 mm thick steel sheet (see Fig. 2 (b)). Then, the profile generated on the steel sheet was measured using a laser (see Fig. 2 (c)). To measure the radial wear, the non grinded part of the sheet was taken as reference. Then, the data obtained is treated to know the different radial wear.
- Grinding force: grinding forces are continuously monitored using the dynamometer. The data captured by the dynamometer are analyzed following the next steps: firstly, the signal of the dynamometer is filtered to reduce noise. Once filtered, the average value of the signal is computed during each grinding pass (approximately 2/3 of the steady-state force signal are used). Figure 3 shows this procedure, as well as an example of force evolution as wear progresses.

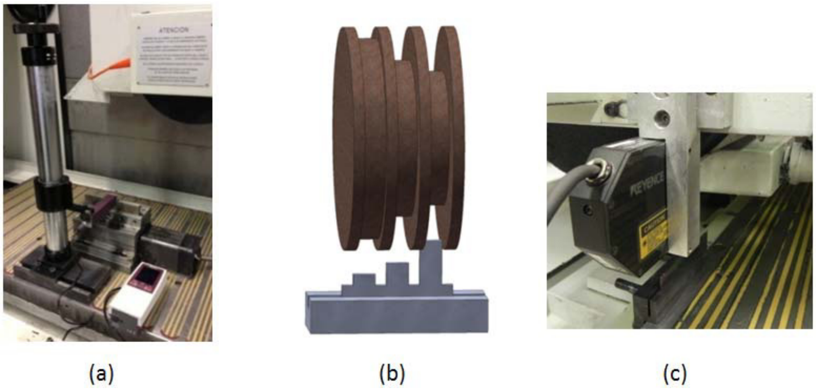


Fig. 2. (a) roughness tester measuring the workpiece surface; (b) replication of the grinding wheel profile on a thin steel sheet; (c) measurement of the radial wear with the laser.

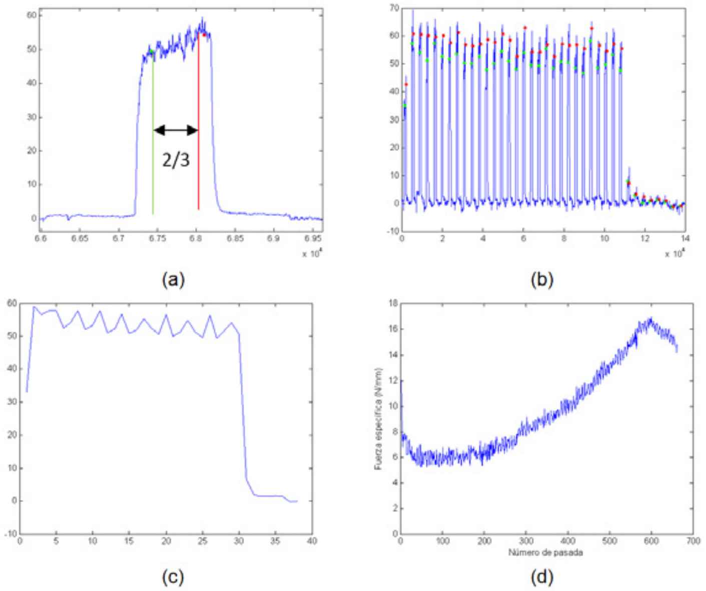


Fig. 3. (a) process force signal for one pass; (b) signal for a repetition of the test (i.e. several passes); (c) average of the forces during one repetition of the test; (d) evolution of average specific forces as wheel wear progresses.

3. Results and Discussion

3.1. Roughness evolution

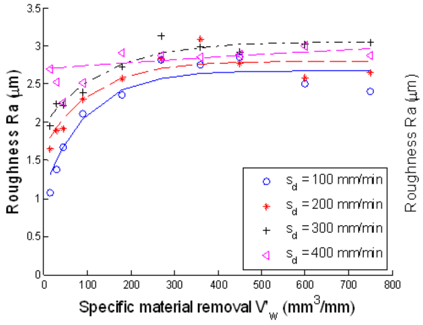
As explained in the introduction, the different dressing conditions generate different roughness values at the beginning of grinding (once the wheel is freshly dressed). This was experimentally observed in these tests too. Also, it was observed that when aggressive grinding conditions were applied (see Fig. 4 (a)) the roughness always tended to worsen until reaching a steady state value i.e. around 2.5 to 3 mm for all cases.

Evolution of roughness when applying soft grinding conditions on the contrary presented different trends depending on the dressing conditions. Soft dressing conditions would worsen the roughness as wheel wear progressed, while more aggressive dressing conditions would tend to improve roughness as wheel wears out (see Fig.4 (b)).

After 500 mm^3/mm of specific material removal, all test with soft grinding conditions produced the same steady-state roughness of around 1 mm. These roughness plots provide information about the initial and the stabilised roughness values at a glance. The initial roughness depends basically on the dressing conditions. The steady-state roughness only depends on the grinding conditions. The reason of this phenomenon is that the wheel topography generated during the dressing gets removed as the grinding process progresses.

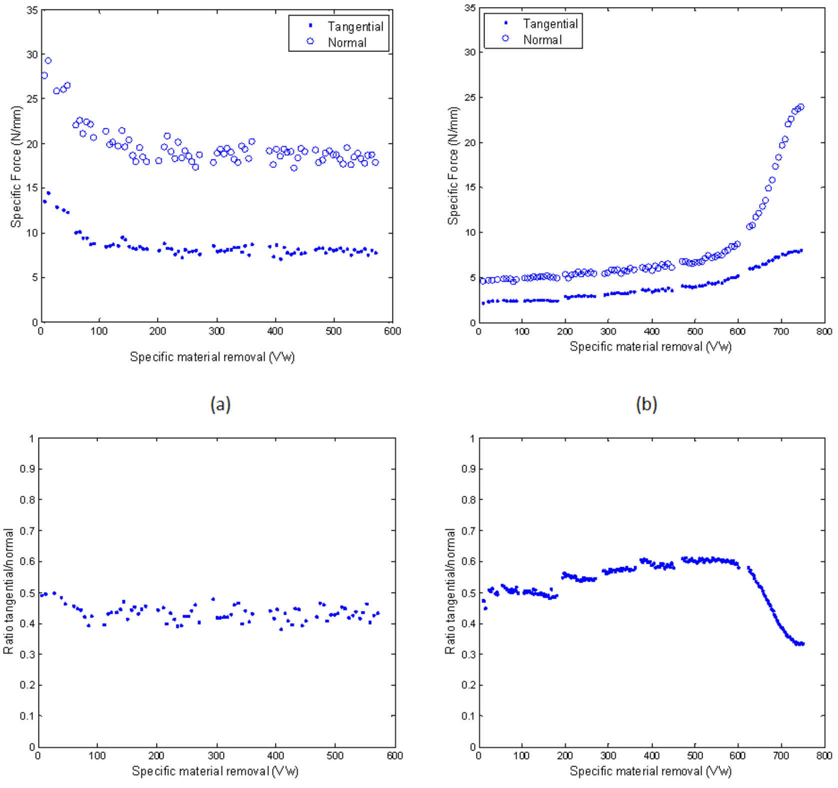
3.2. Forces

The forces of the process were measured in each pass (as shown in Fig. 5). Two kind of evolution were observed, more dependent on the grinding conditions than on the dressing conditions. The aggressive grinding parameters generated an evolution such that the initial force is higher at the beginning of grinding than towards the end, as the force decreased until reaching a steady value. However, the evolution of forces with soft grinding conditions begun with low values just to start raising as grinding progresses. The force increasing slope was moderate in the first passes but it spiked up rapidly towards the end of the test. This slope change or rapid spiking of forces can be more clearly identified if the force ratio between tangential and normal forces is analyzed. As it can be observed in Fig. 5 (d) a drastic force ratio drop occurs when forces (mainly normal force) increase suddenly and it keeps going as no steady-state is achieved in this case.



(a) (b)

Fig. 4. Evolution of roughness for different dressing conditions obtained with: (a) aggressive grinding process conditions and (b) soft grinding process conditions.



(a) (b)

(c) (d)

Fig. 5. Evolution of the forces with aggressive grinding parameters (a) and soft grinding parameters (b). Relationship between tangential and normal forces for aggressive grinding conditions (c) and soft grinding conditions (d).

Such change in grinding force ratio was not observed with aggressive grinding conditions (see Fig. 5) where forces quickly reached steady-state and force ratio remained constant all along the process.

The explanation of this behavior is that when applying aggressive grinding conditions, there is no grinding capacity loss as the process progresses due to the fact that abrasive grains wear through fracture mechanism and new cutting edges arise continuously. On the contrary, with soft grinding conditions, the grinding wheel loses its grinding capacity because the abrasive grains suffer attritious wear and wear flat areas are generated, which increases material ploughing by the grains and consequently requires higher forces to remove material.

3.3. *Radial wear*

Radial wear of the grinding wheel was measured at the end of all tests. Measured radial wear values are summarized in Table 1. The results show that the radial wear depended more on grinding conditions rather than on dressing conditions.

A more detailed monitoring of radial wear was carried out in some of the tests by measuring it at different intervals along the grinding process, so that the evolution of this radial wear could be captured (see Fig. 6). The evolution observed follow two ways depending on the grinding conditions. Circles in blue (a_d=10 μm) and points in red (a_d=20 μm) represent the soft conditions and their radial wear values raise up to 29 and 17 μm respectively. The monitored tests representing aggressive grinding conditions, stars in blue (a_d=10 μm) and crosses in red (a_d=20 μm), reached higher radial wear values of 202 and 209 μm, respectively. This confirmed that radial wear depends significantly more on grinding conditions than on dressing conditions. The magnitudes of radial wear in each case explain the previously mentioned generation of new cutting edges with aggressive conditions (intense and continuous grain and bond fractures that produce a more severe wear of the wheel).

3.4. *Relationship between the measured variables*

A clear relationship between grinding forces and the evolution of part surface roughness was observed. Fig. 7 shows the evolution of surface roughness, grinding forces and radial wear of the grinding wheel under soft and aggressive grinding conditions. As it can be seen, the moments in which the forces and the measured roughness reach steady-state coincide, i.e under soft conditions that value is V_w 500 mm^3/mm.

Table 1. Radial wear of the grinding wheel with different dressing conditions.

Dressing depth of cut (mm)	Grinding Conditions	Dressing feed (mm/min)			
		100	200	300	400
		Radial wear (μm)			
0.01	Soft	29.2	23.1	20.8	24.6
	Aggressive	202.7	215.7	261.5	269.5
0.02	Soft	17.2	20.1	15.3	18.8
	Aggressive	209.6	281.6	234.1	280.1

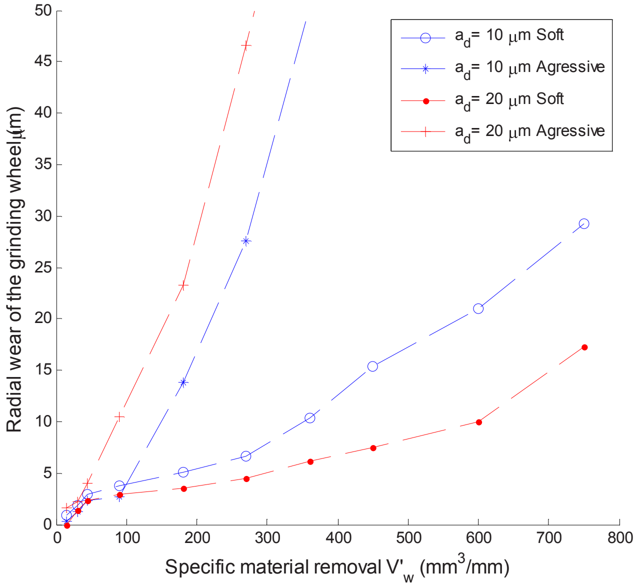


Fig. 6. Evolution of radial wear for different grinding and dressing conditions.

4. Conclusions

The evolution of surface roughness in grinding has been analyzed for different dressing conditions. Aggressive dressing conditions generate coarse grinding wheel topographies. Therefore initial roughness tends to be high and reduces as grinding progresses. Soft dressing conditions generate smoother grinding wheel topographies, so the initial roughness tends to be lower than the final (stable) roughness.

A close relationship between grinding forces and workpiece roughness has been found. Forces and roughness tend to stabilize at the same time; however roughness converges to higher values when aggressive grinding conditions are uses.

It has been also shown that radial wear of the wheel is strongly linked with wheel peripheral topography regeneration. Under aggressive grinding conditions the grinding wheel maintains its cutting capacity due to new grains being continuously arising to the wheel surface. However this occurs by enhancing significantly wheel wear as compared to cases in which soft grinding conditions are applied. In the latter cases, less radial wear takes places due to the fact that the dominant wear mechanism is attrition which is observable at grain level rather than at wheel level. Because of this wear mechanism wear flats grow and grinding efficiency drops as more energy is invested in the material plowing regime.

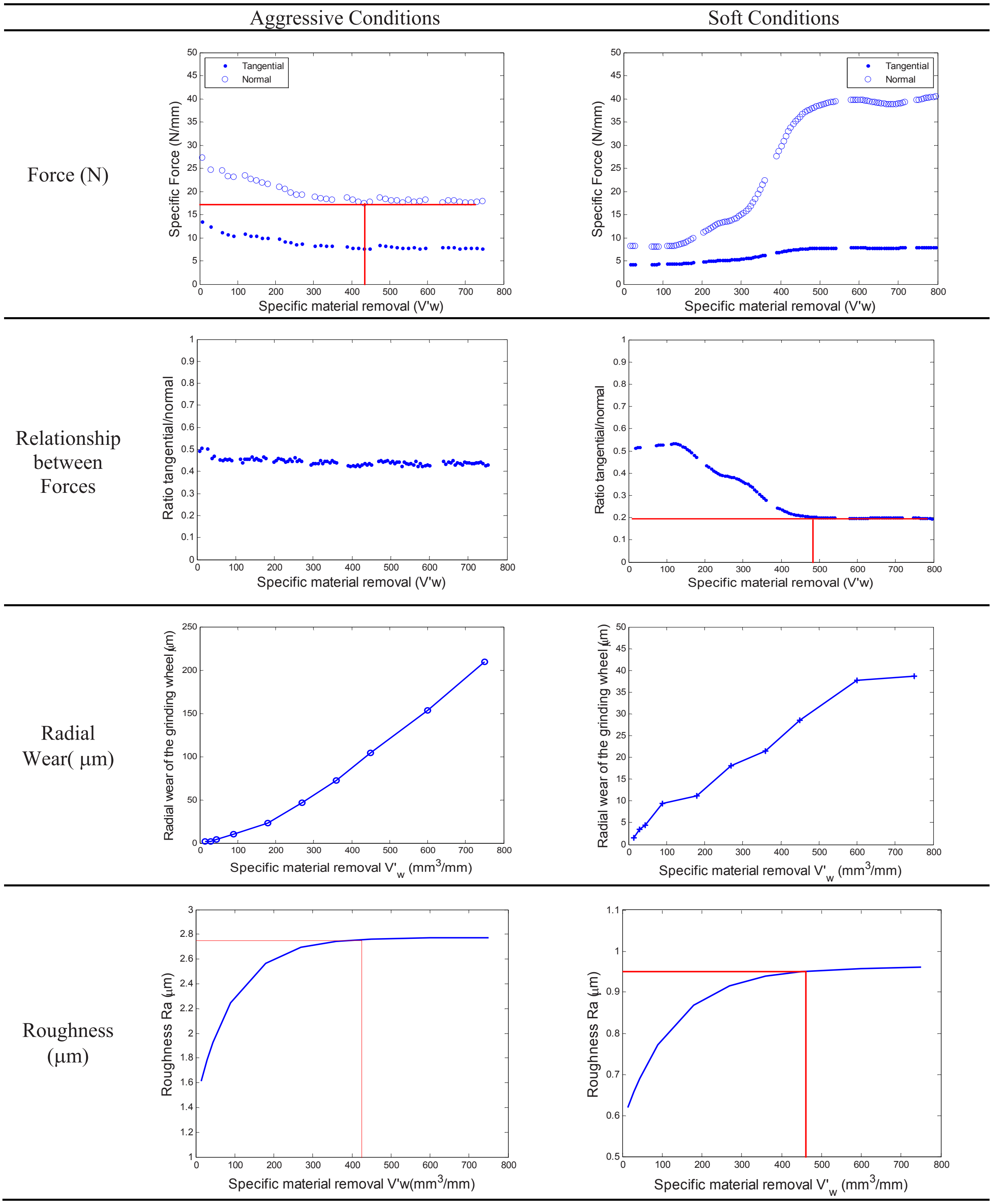


Fig. 7. Evolution of measured variables for different grinding conditions.

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