 DOI: 10.5281/zenodo.14268110

Development of a grinding expert system

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Abstract: Grinding processes are complex and challenging to optimize due to the intricate interplay of numerous parameters. Traditional approaches often rely heavily on operator expertise, leading to variability in results. To address these issues, this paper presents the "Grinding Expert," a system developed at the Institute for Advanced Manufacturing (KSF). The system integrates databases and rule-based algorithms to provide optimal grinding and dressing parameters, significantly improving efficiency and surface quality. Comparative case studies between the Grinding Expert and human experts demonstrate the system's superior ability to optimize grinding processes, resulting in reduced process times and enhanced precision.

I. Introduction

Grinding has a wide range of applications for producing components as a final manufacturing process. Due to the different grinding parameters and their interaction with the product quality, modelling and simulation techniques are mainly unable to select an appropriate combination of process parameters to ensure a reliable and effective design and control of the process. The article presents the Grinding Expert, an expert system for grinding processes developed at the Institute for Advanced Manufacturing (KSF). It offers support for designing and implementing efficient grinding processes by selecting appropriate grinding and dressing tools, parameters, and troubleshooting faulty processes. The system combines databases with rule-based algorithms to provide optimal grinding results.

Achieving the desired grinding performance is a complex task that depends on various parameters, including grinding wheel speed, workpiece speed, depth of cut, and dressing conditions. The skill of the operator usually has a significant impact on the grinding results. To address these challenges, the development of an intelligent decision-making system is a promising approach to reduce uncertainties and improve process performance.

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II. Methods

The Grinding Expert is developed to help machine operators to obtain optimal results in grinding processes right from the start. It consists of a combination of databases (material data, machine data, grinding and dressing tool data as well as some input parameters to determine default data) and a formula-based set of rules, and ensures that efficient grinding processes can be carried out with optimum results. After entering the known parameters (such as workpiece material, target surface quality...), suitable grinding wheels, dressing parameters (including dressing tools) and grinding parameters can be determined via the Grinding Expert (Fig. 1). As a further step, optimization using intelligence (AI) is currently being implemented.

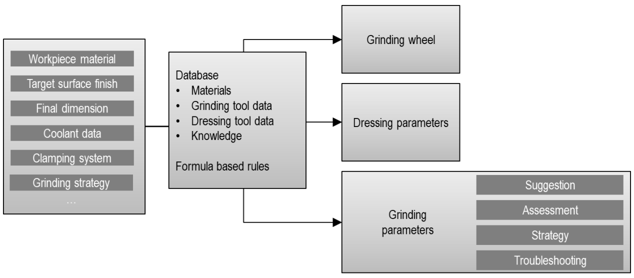

Figure 1: Input parameters, processing and output parameters of the KSF grinding expert system

The modules "Grinding wheel", "Dressing parameters", "Grinding parameters - suggestion, evaluation and troubleshooting" have been described in [1]. In this article the "Grinding parameter strategy" module will be explained in detail.

III. Results and discussion

The "Grinding parameter strategy" menu item can be used to display suggestions for multi-stage process control for external cylindrical longitudinal and plunge grinding, internal cylindrical longitudinal and plunge grinding, and surface pendulum and creep feed grinding, and centerless grinding. The process is divided into several stages, consisting of dressing, roughing, finishing and, if necessary, fine finishing and spark-out (depending on the required roughness, shape accuracy and process stability). After the first grinding process stage (roughing), the infeed and feed rate or the metal removal rate and the workpiece speed for cylindrical grinding are reduced in each subsequent stage until the final dimension is achieved. This procedure enables specified dimensional and form accuracies as well as surface qualities to be achieved.

In the example (**Figure 2**), hardened steel was selected for an external cylindrical grooving process from materials available in the software library (steel, stainless steel,

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nickel and cobalt-based alloys, titanium alloys, aluminium, hard chrome, tungsten carbide, WC-CoCr, ceramics (Al_2O_3 and Cr_2O_3) and rubber). A cBN grinding wheel with vitrified bond, 400 mm diameter and 30 mm wheel width with B107 grit (the system automatically converts the grit to mesh) was selected as the input parameters. The peripheral speed of the grinding wheel was set to 50 m/s (the software recommends selecting the maximum possible cutting speed) and the workpiece diameter was set to 50 mm. Medium requirements were defined for roughness as well as for shape accuracy and stability.

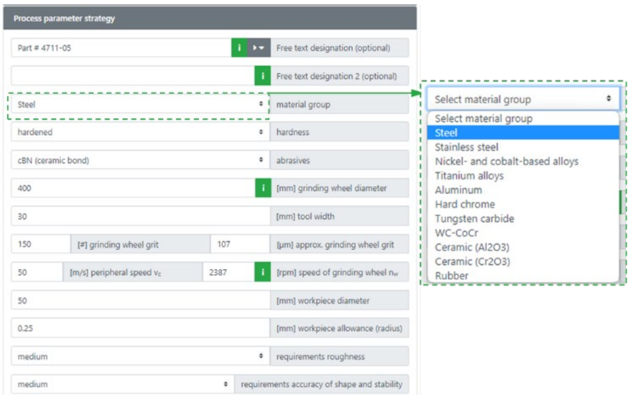
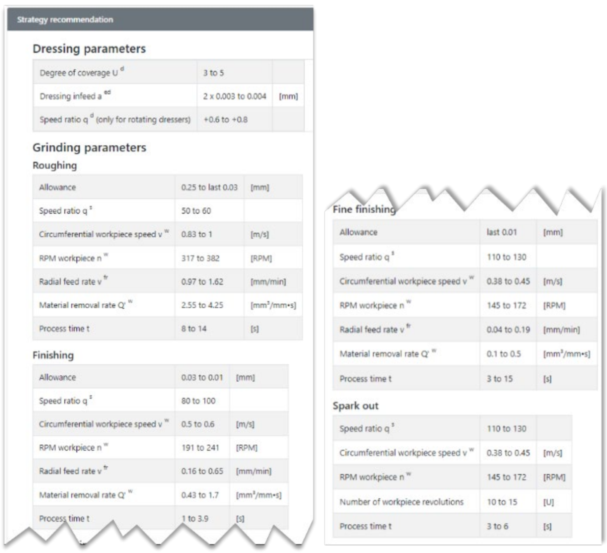


Figure 2: Suggested process parameters for providing the grinding strategy of an external cylindrical plunge grinding process and supported materials

The Grinding Expert suggests a grinding strategy with a 4-step grinding process (roughing, finishing, fine finishing and spark-out) for the selected parameters (Figure 3).



Strategy recommendation

Dressing parameters

Degree of coverage U^d	3 to 5	
Dressing infeed a^{ed}	2 x 0.003 to 0.004	[mm]
Speed ratio q^d (only for rotating dressers)	+0.6 to +0.8	

Grinding parameters

Roughing

Allowance	0.25 to last 0.03	[mm]
Speed ratio q^s	50 to 60	
Circumferential workpiece speed v^w	0.83 to 1	[m/s]
RPM workpiece n^w	317 to 382	[RPM]
Radial feed rate v^{fr}	0.97 to 1.62	[mm/min]
Material removal rate Q'^w	2.55 to 4.25	[mm³/mm•s]
Process time t	8 to 14	[s]

Finishing

Allowance	0.03 to 0.01	[mm]
Speed ratio q^s	80 to 100	
Circumferential workpiece speed v^w	0.5 to 0.6	[m/s]
RPM workpiece n^w	191 to 241	[RPM]
Radial feed rate v^{fr}	0.16 to 0.65	[mm/min]
Material removal rate Q'^w	0.43 to 1.7	[mm³/mm•s]
Process time t	1 to 3.9	[s]

Fine finishing

Allowance	last 0.01	[mm]
Speed ratio q^s	110 to 130	
Circumferential workpiece speed v^w	0.38 to 0.45	[m/s]
RPM workpiece n^w	145 to 172	[RPM]
Radial feed rate v^{fr}	0.04 to 0.19	[mm/min]
Material removal rate Q'^w	0.1 to 0.5	[mm³/mm•s]
Process time t	3 to 15	[s]

Spark out

Speed ratio q^s	110 to 130	
Circumferential workpiece speed v^w	0.38 to 0.45	[m/s]
RPM workpiece n^w	145 to 172	[RPM]
Number of workpiece revolutions	10 to 15	[U]
Process time t	3 to 6	[s]

Figure 3: Suggested grinding strategy for an external cylindrical plunge grinding process

A range of values (from ... to) is suggested in each parameter. It is recommended to start with the conservative values and to increase the values if the process runs well. For the dressing process, a degree of overlap Ud of 3 to 5, a dressing infeed of 2 times 0.003 to 0.004 mm with a speed ratio for rotary dressers of +0.6 to +0.8 is suggested. The appropriate dressing interval must be determined by long-term tests on the machine. Up to a remaining stock allowance of 0.03 mm, a roughing process at a speed ratio of 50 to 60, the workpiece peripheral speed of 0.83 to 1 m/s (workpiece speed of 317 to 382 rpm) and a radial feed rate of 0.97 to 1.62 mm/min are recommended. With these parameters, a specific material removal rate (Q'w) of 2.55 to 4.25 mm³/mm·s and a process time of 8 to 14 s would be estimated. The following finishing process (up to an allowance of 0.01 mm) is proposed with a speed ratio of 80 to 100, the workpiece peripheral speed of 0.5 to 0.63 m/s (workpiece speed 191 to 241 rpm) and a radial feed rate of 0.16 to 0.65 mm/min with a material removal rate of 0.43 to 1.7 mm³/mm·s, giving a process time of 2 to 7 s. The recommendations for the following fine finishing process (last 0.01 mm) would be: Speed ratio 110 to 130, workpiece peripheral speed 0.38 to 0.45 m/s (workpiece speed 145 to 172 rpm) and radial feed rate 0.04 to 0.19 mm/min. With these parameters, the metal removal rate corresponds to 0.1 to 0.5 mm³/mm·s and the process time is 3 to 15 s. Finally, a spark-out process is proposed with a speed ratio of 110 to 130, a workpiece circumferential speed of 0.38 to 0.45 m/s (workpiece speed of 145 to 172 rpm) at 10 to 15 workpiece revolutions or a process time of 3 to 6 s.

The suggestions allow the user to determine the approximate grinding time very quickly and without practical investigations, which is very useful for a simple cost calculation. The software provides this range of parameter within seconds.

In order to validate the Grinding-Expert, several test series were carried out at various industrial companies. The results were consistently very positive, resulting in optimised grinding processes in all cases, which are characterised by improved accuracy at higher stock removal rates, reduced roughness and reduced grinding time. The following case study is an example of a cylindrical grinding process optimised using Grinding Expert.

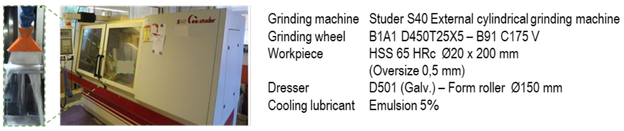


Figure 4: Studer S40 external cylindrical grinding machine and examination parameters

Process parameters before the optimization

Dressing	Dressing infeed a_{ed}		3 x 8 µm
	Dressing speed ratio q_d		-0,4
	Dressing feed rate v_{fad}		130 mm/min
	Grinding wheel peripheral speed v_{cd}		30 m/s
Grinding	Roughing (up to last 0.05 mm allowance)	Cutting speed v_c	30 m/s
		Workpiece rotation speed n_w	145 UpM
		Axial feed speed v_{fa}	1500 mm/min
		Depth of cut a_e	10 µm
	Finishing (up to final dimension)	Cutting speed v_c	30 m/s
		Workpiece rotation speed n_w	145 UpM
		Axial feed speed v_{fa}	300 mm/min
		Depth of cut a_e	5 µm
	Spark out	Strokes	10

Process parameters after the optimization

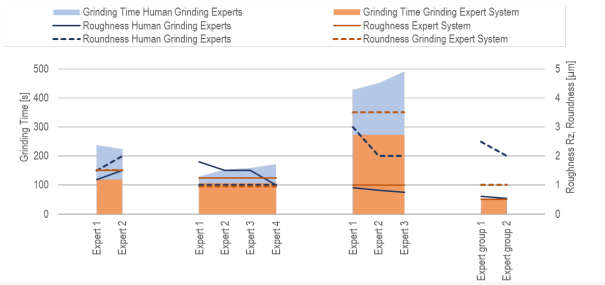
Dressing	Dressing infeed a_{ed}		2 x 4 µm
	Dressing speed ratio q_d		0.4
	Dressing feed rate U_d		3
	Grinding wheel peripheral speed v_{cd}		45 m/s
Grinding	Roughing (up to last 0.05 mm allowance)	Cutting speed v_c (Maximum achievable cutting speed on the machine).	45 m/s
		Workpiece rotation speed n_w	650 UpM
		Axial feed speed v_{fa}	7500 mm/min
		Depth of cut a_e	5 µm
	Finishing (up to final dimension)	Cutting speed v_c	45 m/s
		Workpiece rotation speed n_w	250 UpM
		Axial feed speed v_{fa}	800 mm/min
		Depth of cut a_e	2.5 µm
	Spark out	Strokes	2

Figure 5: Process parameters before and after the optimization

The tests were carried out on a Studer S40 external cylindrical grinding machine (**Figure 4**). The examination parameters, such as workpiece material, workpiece dimensions, specifications, dimensions of grinding wheel and dresser, as well as the cooling lubricant used, are shown in the figure. Prior to optimization, the grinding process was carried out with the parameters shown in Figure 5 (left table).

The surface roughness Rz obtained after grinding before the optimisation was 1.6 – 2 µm. The process was modified by optimisation using Grinding Expert with the parameters summarized in Figure 4 (right table). Optimization with the help of the Grinding Expert **reduced the process time by over 70%.** At the same time, a fine and very uniform surface roughness was achieved, which was **improved to Rz < 1.5 µm**.

Figure 6 shows different grinding processes (case studies 1 to 4) in which the tests were initially carried out with parameters suggested by human grinding experts for the corresponding process. Subsequently, the tests were also carried out with the Grinding Expert. In all tests, the Grinding Expert clearly fulfilled the requirements mentioned. Both in the comparison of the grinding time with the grinding and dressing parameters suggested by the Grinding Expert and with regard to roughness, better results were achieved with the Grinding Expert - except in exceptional cases. In terms of roundness, the human experts were in some cases superior to the Grinding Expert in the given case studies.



	Case study 1	Case study 2	Case study 3	Case study 4
	External Cylindrical Longitudinal Grinding	SlotGrinding	External Plunge Grinding	External Cylindrical Longitudinal Grinding
Grinding Machine	Kellenberger Kel-Varia 2RS 175/1000	Walter Helitronic Vision	Studer S21	Emag HG 204S
Grinding Wheel	B1A1 D500T50X5 B91 C175 V	1A1 200x27x5 – B107 C175 V	D126 C75 B D1A1 400x15	B126C150 D400mm
Dresser	D501 (Galvanized) Form roller Ø150 mm	3A2 125/5 H40 T15 D427 (Galvanized)		D426, one-sided galvanic coating
Material	HSS 65 HRc, Ø19.5 mm Allowance 0.5 mm	HSS	HM, Ø17.5 mm Allowance 5 mm	42CrMoV4 55 HRc, Ø50 mm Allowance 0.1 mm
Requirement	Rz < 2 µm	Rz < 1.5 µm	Ra < 0.2, Rz < 1.5 Runout < 5 µm	Ra < 0.7 Runout < 0.7 µm

Figure 6: Case studies comparing human grinding experts and the Grinding Expert

IV. Conclusions

This paper presents an expert system for the grinding process developed at the Institute for Precision Machining (KSF). The combination of the existing database and developed rule-based algorithms in the proposed system provides the possibility of an optimal grinding process by selecting appropriate grinding and dressing parameters and tools. The presented industrial case study highlighted the robustness of the developed system. The process optimization was achieved in the form of an improvement in the removal rate. The surface roughness after optimization was at least as fine as before optimization, and in some cases, finer surfaces were achieved despite the increased removal rate due to optimization. Comparative case studies revealed that the Grinding Expert consistently outperformed human experts in optimizing grinding processes, leading to more efficient operations, shorter processing times, and improved precision in surface quality.

Acknowledgments

The authors would like to thank the companies Bärhausen GmbH & Co. KG and CNC-Technik Weiss GmbH for the fruitful cooperation that made this work possible.

Author's statement

Research funding: This research has been funded by the German Federal Ministry of Education and Research (BMBF) under grant agreement no. 13FH51041A (CoHMed / Connected Health in Medical Mountains, Impulse Project 04 Digitalization in Medical Technology Manufacturing (DigiMed)). Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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