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Paper

BENCHMARK OF ABRASIVES FOR DIFFERENT APPLICATIONS

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ABSTRACT

The industrial use of abrasive waterjet (AWJ) technology has its strength in the machining of conventionally difficult-to-machine materials where the use of abrasives is obligatory. Since the use of AWJ technology, garnet abrasive has become the standard due to its performance and availability. Facing the impending shortage of natural raw materials, rising prices, and increasing environmental requirements, users of waterjet technology must optimize their processes. A wide range of individual machining tasks and materials to be processed holds great potential for tailoring the consumption of valuable resources and costs in the future.

A fundamental comparison of different abrasive grit is made to contribute to the efficient use of solids for dedicated applications and to identify resource-efficient alternatives. For this purpose, an overview is given of the abrasive performance in AWJ machining. The experiments will be examined for both AWJ cutting through (CT) and controlled-depth machining (CDM) or AWJ milling techniques on two heat-treated modifications of a 42CrMo4 steel alloy. Finally, a fundamental discussion of grit properties on the systematic change of size distribution serves as a basis to meet the requirements of reusability and their attractiveness for future waterjet production.

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1. INTRODUCTION

The effective processing of high-performance materials is vital in all knowledge-based industrial sectors. Similar to all machining approaches, choosing the right tool is fundamental for competitiveness and decides between profit or losses [1]. On par with the resource-effective usage of the tool, resource savings and recycling processes are already upcoming [2]. In addition to the optimization of existing processes, the use of non-conventional alternatives promises high potential in optimization of production [3].

One of the most flexible, non-conventional production techniques for cutting these materials is abrasive waterjet (AWJ) cutting [4]. Cutting through the entire workpiece (CT) has been the standard application of waterjet in the industry since its introduction [5]. In addition, the potential of controlled depth machining (CDM) [6], also known as abrasive waterjet milling, was demonstrated decades ago [7]. Both machining strategies are pioneering for special applications of AWJ technology. Several aspects of tool-material interaction must be considered. For AWJ cutting high-strength materials, the addition of abrasive materials is mandatory [8]. By adopting the abrasives to the material, the waterjet can be used extremely flexible in a variety of machining tasks [9, 10].

With the further spread of water jet technology and the overall growing demand from other industries, the natural resources of garnet abrasives are becoming increasingly scarce. Garnet production has quadrupled in the last 15 years to 1.2 million metric tons per year worth $340 million dollars [11]. The raw material comes from either alluvial (beach) or mining (rock) resources from areas mainly in Australia, South Africa, the United States, China, and India [12]. Since garnet production and export have been increasingly regulated in recent years [13], rising market prices and thus higher costs in production are ubiquitous. In addition, the processing of special materials also produces waste with environmentally critical pollutants - heavy metals and phenols - which were previously discharged directly into the sewage system. Consequently, the cost-efficient recovery and treatment of the waste materials is an obvious and yet necessary challenge to secure the competitiveness of AWJ technology.

Garnets has been used almost exclusively on a one-time basis, although a large proportion can be reused from a technological point of view [13, 13–15]. It is expected that garnet can be partially substituted by alternative materials or recycling. Approximately 50 % of the cast-off garnet grit can be reused [15–17]. Alternative abrasives are promising for special applications [18]. Alternatives can either be of natural origin, e.g. other stone materials, or synthetically produced by melting involved materials, e.g. white fused alumina. However, the involved maintenance costs due high wear on system parts must be considered and ccontamination on the machined surfaces should be well-thought-out [19, 20]. Besides the cost aspect, the origin of raw materials impacts the ecological footprint. Of certain interest are alternatives made of other waste products from industries, e.g. slags from metal production. Nevertheless, the possibility of reuse before final disposal is one possibility to save resources.

2. EXPERIMENTAL SETUP

This study compares different types of abrasives and their erosion performance on a steel alloy. Two categories of abrasives were investigated. First, an assortment of garnet abrasives as a standard for AWJ cutting. Second, a choice of alternatives as a series of natural or synthetic minerals. Natural sources of abrasive grit include garnets from diverse regions of the world. Differences in grain shape and further composition also depend on the extraction method, e.g. whether it originates from mining or alluvial (beach). Alternative abrasives were chosen from different slags as waste products from other industrial branches and natural minerals. All abrasives were selected within a particle size distribution according to #80 mesh. A detailed overview of the average material properties of the garnet abrasives and the alternative abrasives is given in Table 1 and Table 2, respectively. It should be noted that all abrasives have a different bulk density, and the size of individual particles is subject to natural variations. Hence, control sieving was conducted before usage. The individual mass flow was calibrated to $\dot{m}_A = 100$ g/min for all abrasives by check weighing. Here, an H.G.Ridder Type Waricut HWE P2030 5-axis AWJ machine tool in combination with a UHDE Type 6045 intensifier pump was used for experiments. All components of this machine system were controlled by a SIEMENS Type Sinumerik 840D SL CNC control unit. A summary of the machine configuration and individual parametrization is given in Table 3.

A chromium-molybdenum 42CrMo4 steel alloy (AISI 4140) as listed in Table 4 has been chosen as the workpiece material because this steel offers a wide range of either ductile or brittle-hard conditions by heat treatment. This is obtained with the same base material and thus without significant change in material density. Hence, this study does not include other materials. The experiments were carried out by machining two different structural modifications:

- 42CrMo4 +A: Pearlitic structure (annealed, ~ 30 HRC)
- 42CrMo4 +QT: Martensitic structure (quenched, tempered, ~ 55 HRC)

To contribute to future applications of waterjet machining, a comparison is made between waterjet cutting through (CT) the entire workpiece and emerging approaches to controlled depth machining (CDM) techniques as applied to AWJ milling. Both strategies were applied to the specimen as shown in Figure 1. For CT, the cutting performance is evaluated as the cutting ability of a wedge-shaped workpiece with increasing cutting thickness until continuous cutting is no longer possible. The CT cutting performance is then used to discuss the kerf footprints achieved with CDM. Here, the material removal rate (MRR), the maximum height S_z of the surface structure in the kerf bottom as a quality criterion, and the average values of the footprint profile by its width w_P and depth t_P are evaluated to describe the engaged AWJ tool. Visual and optical methods are predominantly used for evaluation. While the CT cut lengths were determined visually, an optical micro coordinate measuring system type Alicona InfiniteFocus G5 was used for the analysis of the CDM footprints following the EN ISO 25178 standard.

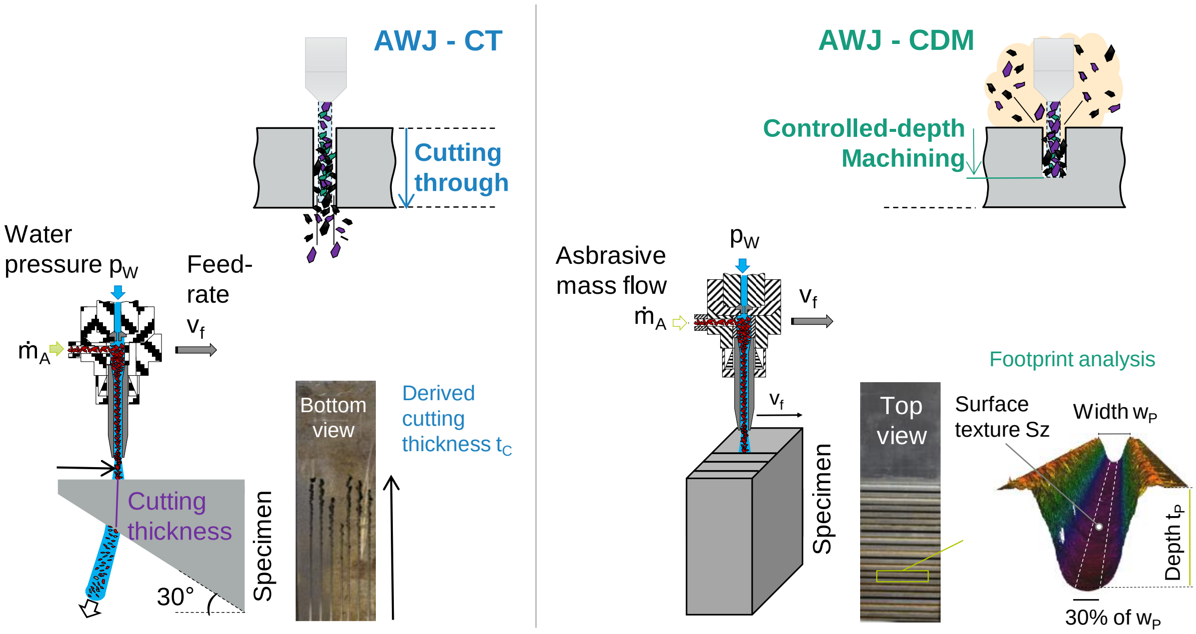

Figure 1: AWJ Machining strategy and experimental procedure. An evaluation was made for cutting through (CT) the entire specimen and analyzation of the AWJ footprint produced by controlled-depth machining (CDM) technique.

Table 1: Machine configuration and parametrization for CT and CDM experiments.

Machine configuration	***CT Parametrization***	***CDM Parametrization***
$\emptyset d_O = 0.250\ mm$	$p_W = 400\ MPa$	$p_W = 400\ MPa$
$\emptyset d_F = 0.76\ mm$	$\dot{m}_A = 100\ g/min$	$\dot{m}_A = 100\ g/min$
$SoD = 4\ mm$	$v_F = 25\ mm/min$	$v_F = 1250\ mm/min$

Table 2: Physical properties and composition of garnet abrasives.

	Beach SA	***Beach AU***	***Rock US***	***Rock CN***
Hardness	7.5-8.0 mohs	7.5-8.0 mohs	7.5-8.5 mohs	7.5-8 mohs
Grain shape	sub angular	sub angular	angular	angular
Specific weight	4.1 g/cm³	4.1 g/cm³	4.0 g/cm³	4.0 g/cm³
Composition	95 % Almandine 1 % Pyroxene 5 % Ilmenite	93 % Almandine 5 % Pyroxene 1 % Ilmenite	94 % Almandine, Pyrope, Grossular 6 % other minerals	90% Almandine 5% Pyroxene 2% Ilmenite

Table 3: Physical properties and composition of alternative abrasives.

	Coal Slag	**Copper Slag**	**Steel Slag**	**Granite**	**Grey-wacke**	**Olivine**
Hardness	7 mohs	6.5 mohs	7.5 mohs	7 mohs	7 mohs	7 mohs
Grain shape	angular	iso-metric	angular	sub angular	sub angular	sub angular
Specific weight	2.5 g/cm^3	3.6 g/cm^3	3.6 g/cm^3	3.3 g/cm^3	3.3 g/cm^3	3.3 g/cm^3
Composition	50 % SiO_2 28 % Al_2O_3 9 % Fe_2O_3 6.5 % CaO 2.5 % CaO 2.5 % CaO	53 % FeO 6 % Al_2O_3 5 % CaO 1 % K_2O 2 % MgO 1 % S	32 % SiO_2 29 % Al_2O_3 20 % MgO 10 % Cr_2O_3 5 % Fe_2O_3 4 % CaO	50 % Orthoclase, potassium feldspar 20 % Plagioclase feldspar 20 % Quartz 10 % Biotite	40 % Quartz 35 % Feldspar 15 % Mica 10 % Chlorite, carbonates	48 % MgO 40 % SiO_2 11 % FeO 1 % Al_2O_3

3. EVALUATION OF RESULTS

A comparison of the cutting performance for abrasive waterjet (AWJ) was made for each abrasive grit on two heat-treated modifications of an 42CrMo4 specimen by either AWJ cutting-through (CT) the entire workpiece or by an analysis of the footprints created by controlled-depth machining (CDM), like waterjet milling. In the pursuing evaluation of the experiments, several aspects of the involved material interaction must be considered. Both the kinetic and physical properties of the abrasive particles interacting with the workpiece material were known to be of fundamental importance for erosion. Therefore, a basic distinction should be made between the stress on the abrasives in CT, mainly due to sliding wear, and CDM correspondingly due to impact wear. Since this approach serves as a reference for further investigations on abrasive properties in AWJ machining, trademarks or brand names have been omitted. Instead, the type and origin of the abrasive was indicated.

In the first section of the CT assessment, a reference value was first determined within the garnet abrasives. Here, the percentage deviations of the most performant garnet abrasive were used. An average value was then taken from the garnets, which was then used as the new reference value for evaluating the alternative abrasives. The respective reference values were formed within a material modification and only used within it. In the second section of the CDM assessment, a similar procedure was followed. To benchmark alternative abrasives, a direct comparison was made against the garnet abrasives as being the standard in waterjet technology.

3.1 CT performance

In the first section of the evaluation, the cutting performance of common garnet abrasives was considered and compared with alternative abrasive materials. Other evaluation criteria, such as the characteristics of jet lag, the formation of burrs at the exit, or the edge quality, were not part of this study. Instead, a reference of enrolled garnet abrasives was selected by the most performing garnet within a modification of the 42CrMo4 steel.

The annealed 42CrMo4 +A (Figure 2 left) reveals a very similar cut-off capability for garnet abrasives. The US-origin rock garnet (Rock US) was the best performing abrasive, corresponding to a cutting thickness t_C = 36.1 mm. It serves as a reference in the following comparison, closely followed by the Australian beach garnet (Beach AU) with about 98.1 % ability of its predecessor. This was immediately followed by South African beach garnet (Beach SA) with about 94.7 % cutting performance in comparison and Chinese rock garnet (Rock CN) of 91.7 % respectively. Overall, the differences within the 42CrMo4 +A were in the range of approx. 8 % among each other and most likely within the range of natural fluctuations. On the other hand, deviations from the previous result were obvious at the quenched and tempered 42CrMo4 +QT (Figure 2 right). Although the previously rated high-performance garnets were also in the upper range of the cutting performance here, the type of material extraction was conspicuous. Both representatives of the mined rock garnet were above those from beach exploitation in their performance. Compared to the best-performing Rock CN with a cutting thickness t_C = 29.0 mm (reference) and Rock US (98 %), the Beach AU (96.5 %) was slightly ahead of the Beach SA (91.4 %). Despite the slightly different results and the overall reduced cutting performance at 42CrMo4 +QT, the range of deviations among each other was in a similar order of magnitude as for the previous 42CrMo4 +A.

The evaluation of alternative abrasives considered the average value within the preceding material modification of garnets as reference. This allows the comparison of the respective abrasive with the typical result of a garnet. Alternative abrasives were grouped into synthetically produced fused slags and natural minerals or stones. Melted Coal Slag is a synthetic mineral resulting from energy production by coal combustion. Copper Slag or copper silicate slag is produced from the corresponding melting process. Similarly, Steel Slag matches to a waste product in iron production. On the side of natural minerals, local rock types were also considered. Granite has hardly been used as an abrasive so far and is mainly used in the construction sector, as is Greywacke. Olivine, on the other hand, is a naturally occurring metal silicate from mining areas in India and China, which is also used industrially as an abrasive.

When cutting 42CrMo4 +A with the alternatives (Figure 3), the group of slags was fundamentally below the average performance of the garnets ($\overline{t_C}$ = 30.3 mm), but still above the natural minerals. Coal Slag was in first place with an equivalent to the garnet reference of 85.7 %, immediately followed by Steel Slag and Copper Slag (79.1 % and 73.9 %, respectively). For the natural minerals, Olivine still achieves 58.8 %, with Granite and Greywacke again halving the cutting performance further to around a third to that of garnets (31.3 % and 29.7 %, respectively). On the other hand, at the

42CrMo4 +QT, the group of slags performs similarly, although in some cases the differences become more obvious. Here, the reference value for comparison was t_C = 20.0 mm. The Steel Slag was in first place with 83.8 %, followed by Copper Slag and at a greater distance Coal Slag (66.7 % and 46.3 %, respectively). However, Olivine performs slightly better than on the annealed counterpart (62.0 %), as does Granite (32.4 %). Greywacke achieved a further drop with only 25 % compared to the garnet reference.

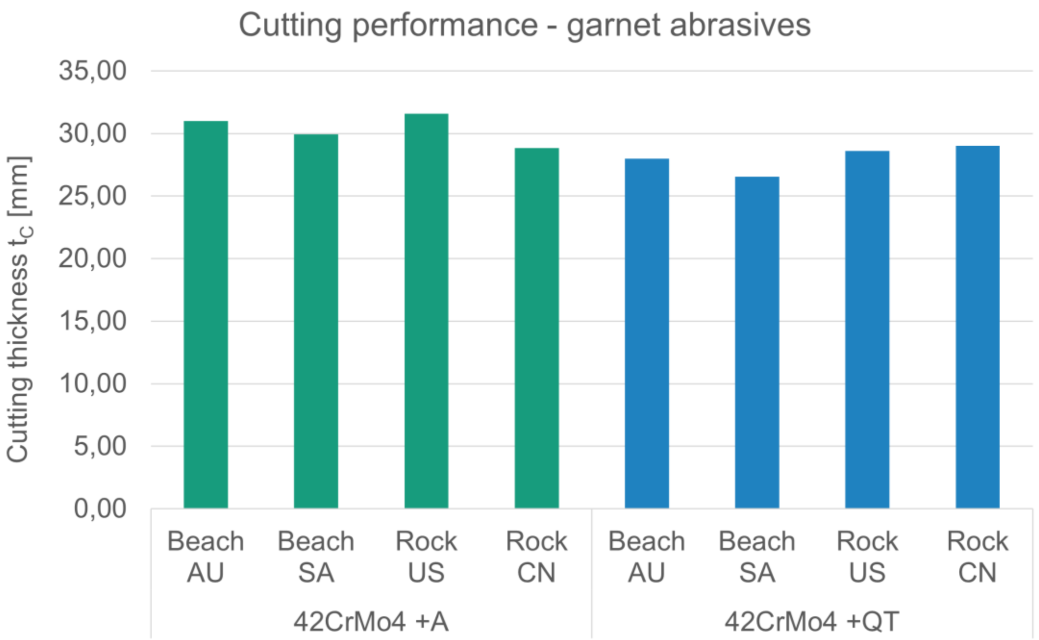

Figure 2: Cutting through (CT) performance of garnet abrasives. Derived cutting thickness t_C on a heat-treated 42CrMo4 steel. The results on the annealed 42CrMo4 +A are on the left side, the quenched and tempered 42CrMo4 +QT is on the right.

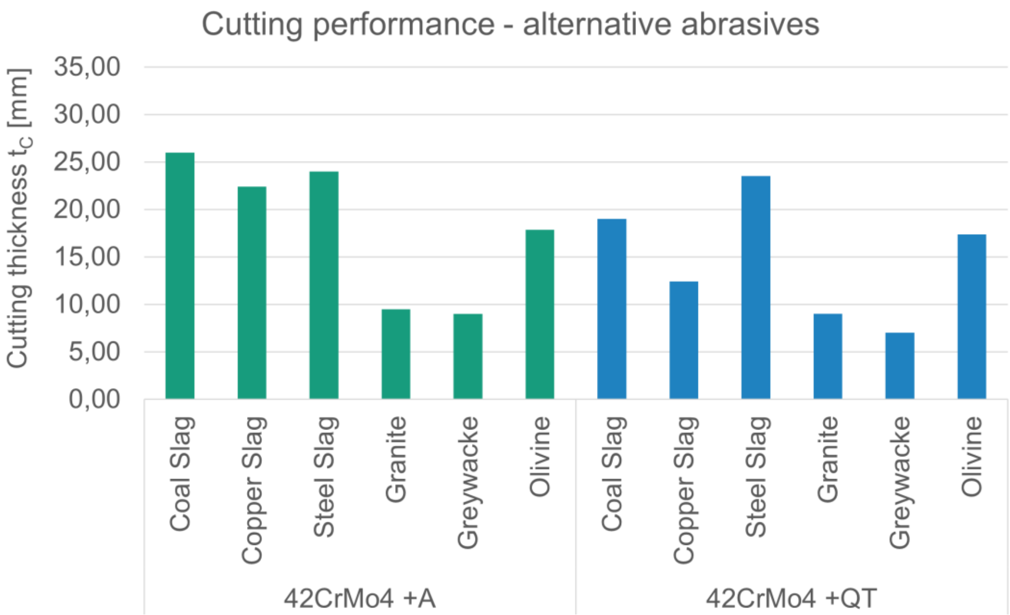

Figure 3: Cutting through (CT) performance of alternative abrasives. Derived cutting thickness t_C on a heat-treated 42CrMo4 steel. The results on the annealed 42CrMo4 +A are on the left side, the quenched and tempered 42CrMo4 +QT is on the right.

As an intermediate conclusion for the CT experiments, the garnet grits performed very similar at the respective material. The results only slightly differ according to the composition and physical properties of the abrasives. On the 42CrMo4, the mined rock garnets, typically characterized by sharp grains, performed above their alluvial counterparts. An initial difference could be made to their origin and exploitation method. However, the results quantified possible alternatives for substitutes. Here, the results differed more depending on the material modification of the specimen in contrast to the physical properties of the abrasives. The slags were distinguished by sharp grains, but with lower hardness compared with their counterparts. In the scope of AWJ CT, the garnet grit represents a reference against which alternative abrasives must measure themselves.

3.2 CDM characteristics

In analogy to the CT experiments, the results achieved with the garnet abrasives were compared categorically for CDM. Once, the category of garnet abrasives was first compared with each other. Then the alternative abrasives were benchmarked with the average of the garnets within a modification of the 42CrMo4 as a reference. In addition to the determination of the cutting performance based on the material removal rate (MRR), the machining quality was characterized here based on the maximum height S_z of the derived profile at the bottom of the footprint. The lower this value, the more uniform the achieved erosion, which corresponds to better surface texture. Basic information on the engaged AWJ tool geometry was finally derived by depth t_P and width w_P of the footprint.

The MRR on the ferritic-pearlitic microstructure of the annealed 42CrMo4 +A by CDM revealed a comparable ranking of the garnet abrasives as on the CT counterpart (Figure 4). In terms of performance, the rock garnet from the US (Rock US) was again in first place with an average MRR of around 545 mm^3/min and served as the reference on this material modification. The second highest result of 85 % was already about a quarter below this value and was achieved by the Australian beach garnet (Beach AU). The other two garnet abrasives were grouped close together in terms of removal rate. The Chinese rock garnet (Rock CN) achieved around 71.3 % of the reference value, while the South African beach garnet (Beach SA) achieved 62.6 %. On the martensitic structure of the quenched and tempered counterpart 42CrMo4 +QT, however, the mined Rock CN set the reference utilizing an average MRR of around 465 mm^3/min against the result of the also mined Rock US. The alluvial Beach AU and Beach SA were again quite a bit below in terms of machining performance, with 73.7 % and 69 %, respectively.

Deviating from the previous results, the characterization of the surface texture achieved with garnet grit by the maximum height S_z behaved detached from the CT performance (Figure 5). On the 42CrMo4 +A, a very uniform erosion due to the lowest S_z = 359 µm was achieved with Beach AU. This corresponds to only 56.5 % of the corresponding reference from the MRR results set by Rock US. Analogously, a correlation between the grain structure of alluvial and mined garnet was found. Beach SA (73.3 %) and Rock CN (154 %) varied further to reference. However, on the

42CrMo4 +QT the overall differences of S_z were significantly higher. Here, the reference value of Rock CN forms a minimum (S_z = 218 µm). Contrary, the result of the mined counterpart Rock US revealed a maximum of 271 %. The two remaining Beach AU and Beach SA were close together in the midfield with 205.6 % and 208.2 %, respectively.

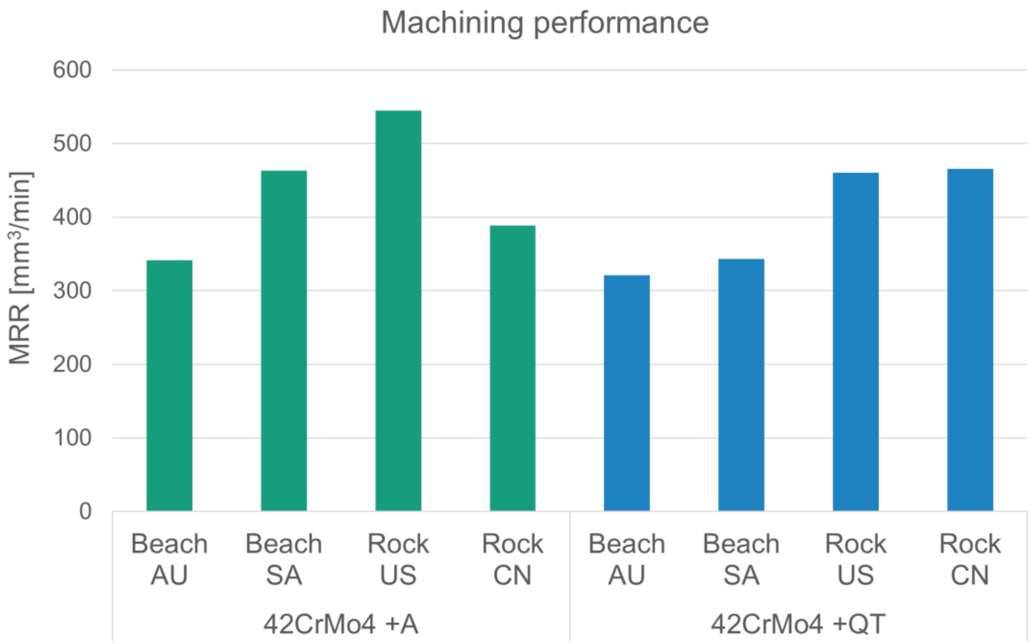

Figure 4: Controlled-depth machining (CDM) with garnet abrasives. Machining performance by material removal rate (MRR) on a heat-treated 42CrMo4 steel. The results on the annealed 42CrMo4 +A are on the left side, the quenched and tempered 42CrMo4 +QT is on the right.

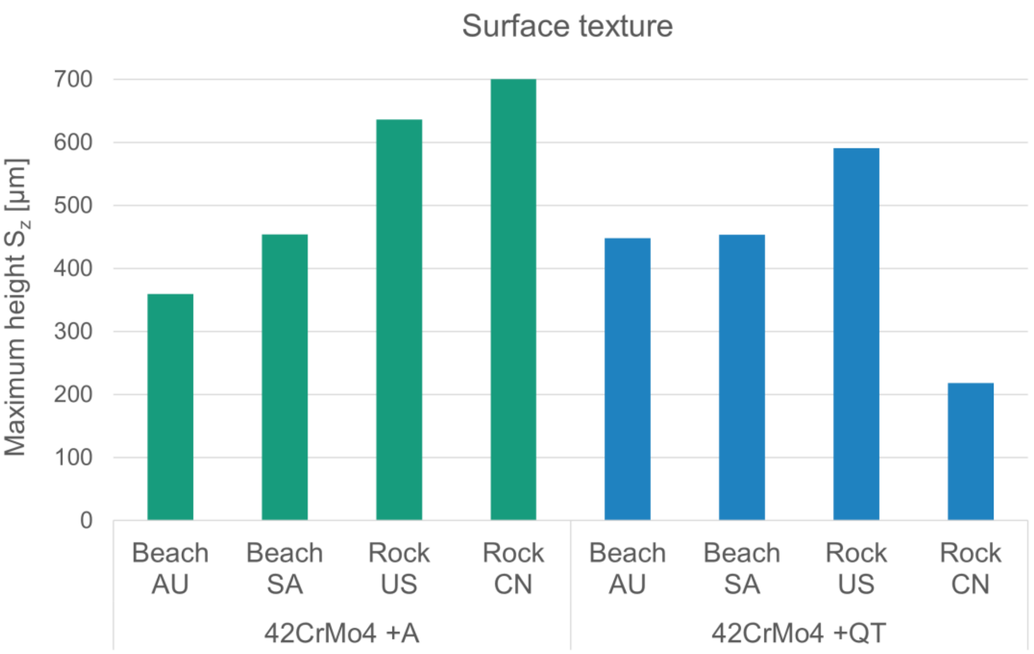

Figure 5: Controlled-depth machining (CDM) with garnet abrasives. Surface texture by the maximum height S_z on a heat-treated 42CrMo4 steel. The results on the annealed 42CrMo4 +A are on the left side, the quenched and tempered 42CrMo4 +QT is on the right.

The geometric dimensions of the footprints (Figure 6) by the mean depth t_P achieved with garnets on 42CrMo4 +A were predominantly in line with the associated courses of MRR. For both Beach AU (65.3 %) and Rock CN (62.2 %), the deviations to the reference Rock US (t_P = 732 µm) were practically identical. Beach SA with a ratio of 116.5 % revealed a slightly more pronounced depth in comparison. However, the corresponding results on the 42CrMo4 + QT varied more. The reference Rock CN (t_P = 440.0) previously set in the CT evaluation was approximately on par with Beach AU (102.8 %) on this hardened material modification. In contrast, the Rock US (181.8 %) and the Beach SA (194.0 %) achieved significantly greater depth values. Although the mean widths w_P on the 42CrMo4 +A showed only slight fluctuations within 3.6 % above the reference value, however, a minor reduction to smaller values within 3 % was found on the 42CrMo4 +QT.

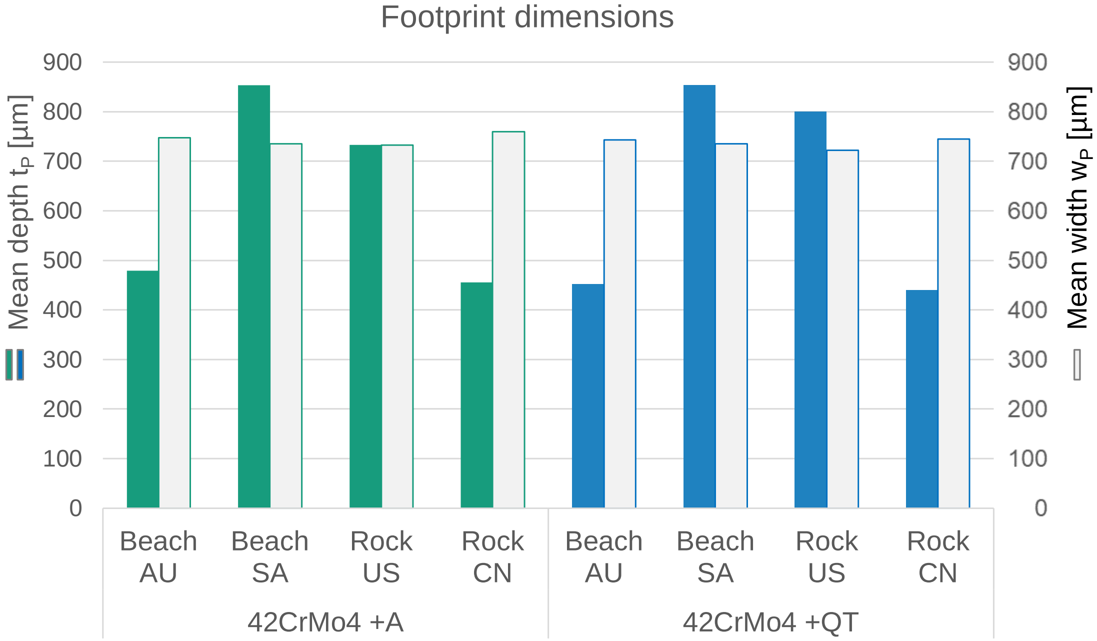

Figure 6: Controlled-depth machining (CDM) with garnet abrasives. Footprint dimensions by the mean depth t_P (left column) and the mean width w_P (right column) on a heat-treated 42CrMo4 steel. The results on the annealed 42CrMo4 +A are on the left side, the quenched and tempered 42CrMo4 +QT is on the right.

A comparison of the performance of alternative abrasives by MRR was similarly done with the average value of garnet grit on the respective material modification as a reference (Figure 7). Strong differences to the previous CT results were evident here. On the 42CrMo4 +A machined with the synthetic minerals, both the Coal Slag (63.3 %) and the Steel Slag (62.1 %) showed a similar performance equivalent to the garnet reference ($\overline{MRR}$ = 434.4 mm^3/min). The Copper Slag (22.4 %) was inferior and almost on par with Granite (21.4 %) and Olivine (20.4 %). Greywacke (11.4 %) showed a strikingly low performance here. However, a significant performance decrease was also observed on the martensitic 42CrMo4 +QT. Both the Coal Slag (7.2 %) and the Copper Slag (2.1%) showed a strong decline in MRR in comparison to the associated garnet reference ($\overline{MRR}$ = 397.3 mm^3/min). However, the Steel Slag still performed similarly well (62.2 %) here, so did Granite (19.7 %). The remaining Greywacke

(6.4 %) and Olivine (7.4 %), also suffer a significant decrease in removal rate. It gave the impression that some results between the materials behaved in opposite ways.

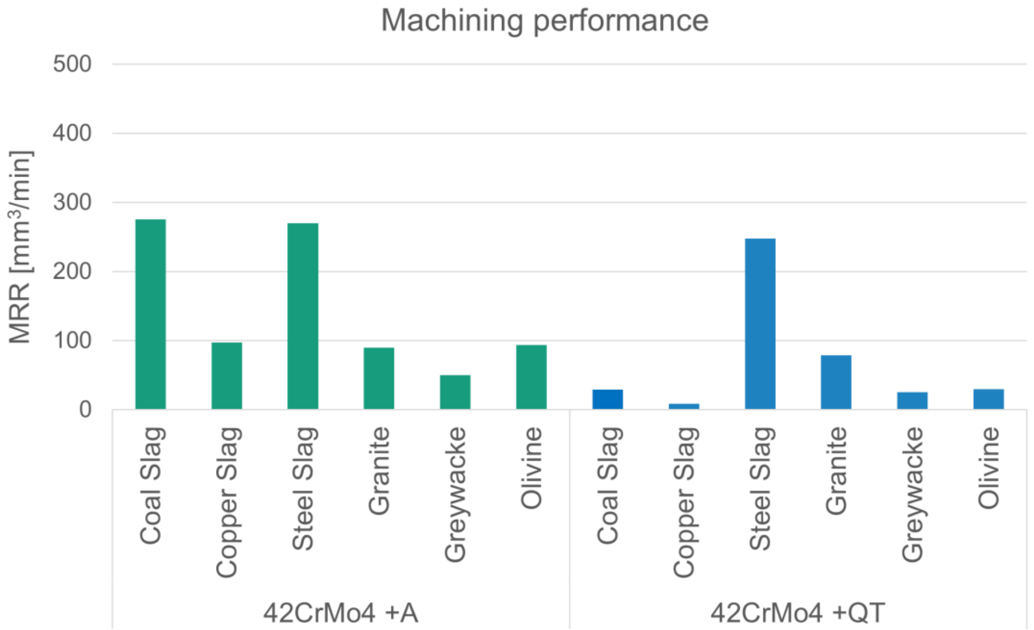

Figure 7: Controlled-depth machining (CDM) with alternative abrasives. Machining performance by the material removal rate (MRR) on a heat-treated 42CrMo4 steel. The results on the annealed 42CrMo4 +A are on the left side, the quenched and tempered 42CrMo4 +QT is on the right.

In the evaluation of surface texture, all alternative abrasives showed a significant reduction of the maximum height S_Z (Figure 8). On the 42CrMo4 +A, the values of S_Z in the group of slags were very close. Here, the equivalent to the garnet reverence ($\overline{S_Z} = 608.3\ \mu m$) was 37.1 % for Coal Slag, 35.8 % for Copper Slag and 39.5 % for Steel Slag. Slightly above, but still below the garnet grit, were Olivine with 45.9 %, Granite with 65.3 %, and finally Greywacke with 77 %. On the 42CrMo4 +QT, one exception was achieved with Steel Slag (14.6 %) against the reference value of $\overline{S_Z} = 429.5\ \mu m$. The remaining minerals minimized the results of S_Z on this material further: Coal Slag (1.7 %) and Copper Slag (0.5 %) showed very good results, and Greywacke (1.5 %) and Olivine (1.7 %) had comparable expressions, followed by Granite (4.6 %).

The footprint dimensions for alternative abrasives were strictly following the corresponding MRR results (Figure 9). On the 42CrMo4 +A, the average depth t_P achieved with the slags in comparison with the garnet reference ($\overline{t_P} = 630.3\ \mu m$) was 26.5 % for Copper Slag, 71.7 % for Steel Slag and 75.1 % for Coal Slag, respectively. A lower depth t_P was achieved when using natural minerals, equivalent to 12.5 % for Greywacke, 21.9 % for Granite and 28 % for Olivine. The corresponding results on the 42CrMo4 +QT were even closer. Here, the reference was $\overline{t_P} = 636.5\ \mu m$. The group of slags corresponded to 2.7 % for Copper Slag, 6.9 % for Coal Slag and 64.1 % for Steel Slag. A further deviation, but with overall lower values, were achieved for Greywacke (6.8 %), Granite (19.4 %) and Olivine (8.9 %). However, the corresponding values of the mean kerf width w_P were practically on par with those of the garnet grit.

On the 42CrMo4 +A, the deviations against the garnet reference ($\overline{w_P} = 744.0\ \mu m$) were within +/- 2 %. For 42CrMo4 +QT, the majority was within +/-3 %. Here, an exception was found for Copper Slag, which was 9% smaller than the garnet reference $\overline{w_P} = 736.2\ \mu m$.

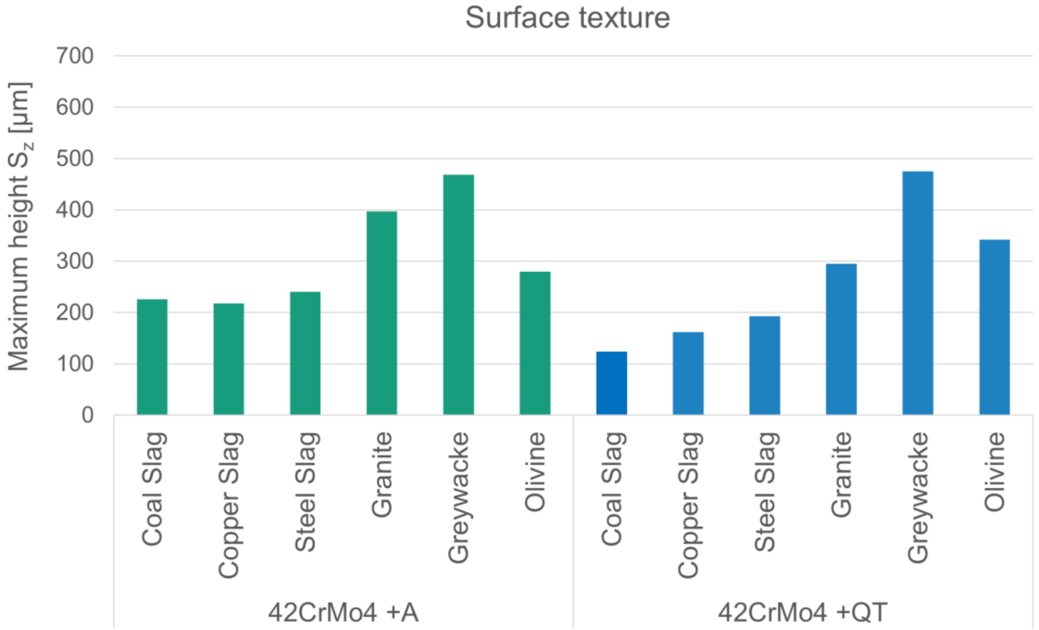

Figure 8: Controlled-depth machining (CDM) with alternative abrasives. Surface texture by the maximum height S_z on a heat-treated 42CrMo4 steel. The results on the annealed 42CrMo4 +A are on the left side, the quenched and tempered 42CrMo4 +QT is on the right.

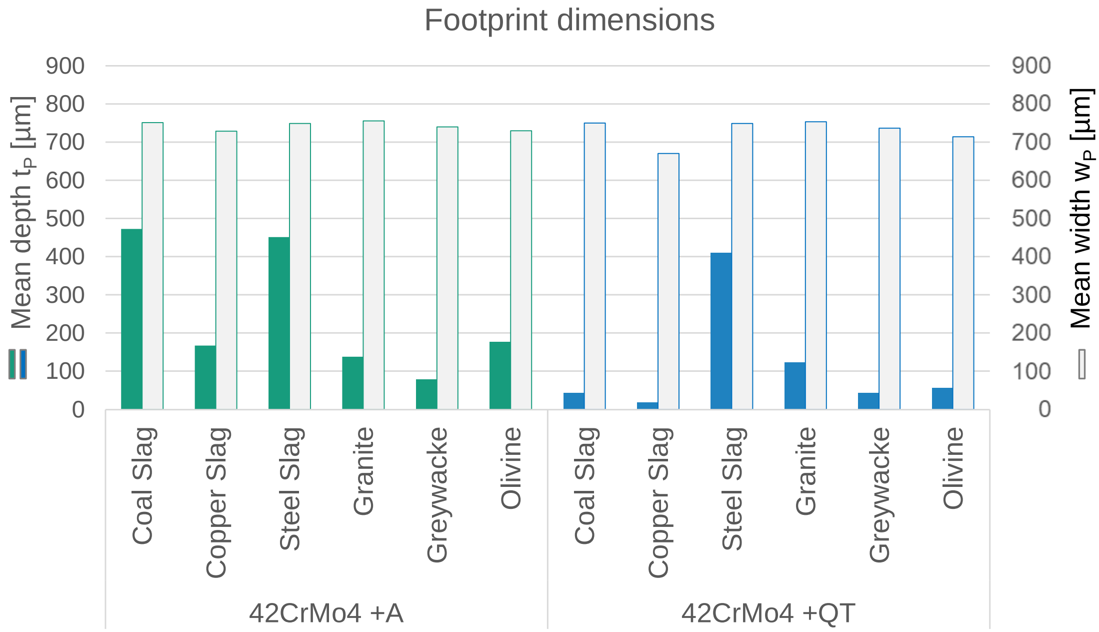

Figure 9: Controlled-depth machining (CDM) with alternative abrasives. Footprint dimensions by the mean depth t_P and the mean width w_P on a heat-treated 42CrMo4 steel. The results on the annealed 42CrMo4 +A are on the left side, the quenched and tempered 42CrMo4 +QT is on the right.

In the interim conclusion for CDM, the assessment of the findings stood out at some points. Firstly, the garnet abrasives behaved in a fundamentally similar way to CT, although the contrasts were more pronounced at CDM. Consequently, the optimization potential for certain applications became even more obvious. Although the high MRR of the garnet abrasives could not be achieved here, the considered alternatives nevertheless convinced with better surface texture. The results revealed a high potential of using alternative abrasives in AWJ machining. However, an inferior performance on the experimental conditions of this study does not necessarily mean a final rating of alternative abrasives. For example, a less performing abrasive here could be competitive with other materials, for example when cutting fibre-reinforced plastics or non-ferrous metals.

4. SUMMARY AND OUTLOOK

In this study, a fundamental benchmark on different abrasives was conducted experimentally. The aim was to rate different sources of natural and synthetic minerals for a resource-efficient approach in abrasive waterjet (AWJ) technology, here by machining a 42CrMo4 steel alloy of two structural modifications by heat treatment. By either ductile or brittle properties of the workpiece material, a comparison was made between cutting through (CT) the entire workpiece and controlled-depth machining (CDM), often referred to as waterjet milling.

The evaluation of this study highlighted the optimization potential when using different abrasives in various applications of AWJ. For a practical benchmark of abrasives, a reference was proposed in comparison with an average of the typical garnets. The cutting performance in CT with garnets was very similar and on par with MRR in CDM on the considered material. However, it was shown that alternative abrasives showed great potential towards a stable, high-quality process for CDM strategies or could act as an add-on to garnets to gain economic application. At the same time, by including waste products from other industries, a contribution to resource-savings in AWJ machining was made.

In the future, this study will be extended toward the reusability of abrasives. To benchmark the closed-loop capability, the systematic distribution of particle sizes [17] and the abrasive wear after workpiece contact must be considered. The abrasives should also be examined to hold the permissible limits for discharging wastewater. To be on time with upcoming regulations, the corresponding treatment of wastewater should be integrated into waterjet machines on a manufacturer level. Further experiments should be conducted to characterize the machining result, e.g. by the constriction of the engaged AWJ tool or by surface integrity aspects. The approach of this study to rate against a garnet reference could serve as a basis to identify alternative abrasives and benchmark them on other materials.

5. ACKNOWLEDGMENTS

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7. NOMENCLATURE

AWJ	Abrasive Water Jet
CT	Cutting through
CDM	Controlled-depth machining
HRC	Hardness Rockwell
$\emptyset \boldsymbol{d_O}$	Orifice inner diameter in mm
$\emptyset \boldsymbol{d_W}$	Focus tube inner diameter in mm
SoD	Stand-off distance in mm
$\dot{m}_A$	Abrasive mass flow in g/min
p	Water pressure in MPa
v_F	Feedrate in mm/min
t_C	Derived cutting thickness in mm
MRR	Material removal rate in mm^3/min
S_z	Maximum surface height in µm
w_P	Width of the profile in µm
d_P	Depth of the profile µm
$\overline{t_C}$	Derived cutting thickness in mm
$\overline{MRR}$	Average material removal rate of garnets as reference in mm^3/min
$\overline{S_Z}$	Average maximum surface height of garnets as reference in µm
$\overline{w_P}$	Average width of the profile of garnets as reference in µm
$\overline{d_P}$	Average depth of the profile of garnets as reference µm