Fundamental abrasive contact at high speeds: scratch testing in experiment and simulation

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Fundamental abrasive contact at high speeds: scratch testing in experiment and simulation

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Abstract: The understanding and experimentation of abrasive wear mechanisms at high speeds is still poorly investigated in literature. This is mainly due to a lack of suitable, well-instrumented test rigs for fundamental, single abrasive wear events. Standard scratch tests, which are often utilized for studies of abrasion phenomena, operate in the low-speed range up to some mm/s, while applications suffering from abrasive wear often operate at speeds exceeding 1 m/s (e.g., rolling, grinding, machining). Numerical approaches, especially particle-based methods, allow the simulation of such fast deformation processes, but rely on hardening models that require a precise knowledge of material parameters. Thus, the Johnson-Cook material model was parametrized using data from high-speed compression tests of pure aluminum. A series of scratch tests with increasing depths were then simulated using the particle-based Material Point Method (MPM). Experimentation was done on a pendulum scratch test rig equipped with a Rockwell C diamond cone. By adjusting the balance point of the swing arm of ~1 m length, a velocity of 6.8 m/s was achieved at its tip as measured with a high-speed camera. Scratches of several depths were performed, and their force signals acquired. Post-test analyses comprised topography measurements and EBSD on cross-sections of the scratches to investigate the microstructural changes due to the high-speed wear event. Scratch topographies and abrasive mechanisms compared favorably between experiment and simulation for the aluminum. The extent of strain hardening was significantly reduced compared to low-speed experiments. The calibration of the high-speed force sensor was successful and now allows the investigation of new alloys and determination of material parameters under high-speed abrasive conditions.

Keywords: Abrasion; Scratch; Numerical Simulation; High-Speed

1. Introduction
Wear mechanisms at high speeds are relevant for a vast number of industrial applications that range from machining and manufacturing processes such as rolling, grinding, or tooling to material transportation, among others. One of the main challenges that such applications impose is the difficulty of studying the interacting surfaces directly and the study of the in-situ phenomena developed in the surface and subsurface regions of the materials. Therefore, simulation techniques are becoming increasingly relevant tools to complement the understanding of the underlying processes such as microstructural changes and wear mechanisms. Among the available simulation techniques, the Finite Element Method (FEM) is one of the most developed, but when dealing with large deformations the mesh distortion becomes a severe issue and re-meshing makes the models computationally expensive [1]. In this light, meshless methods constitute an attractive solution and particularly the material point method (MPM) is an approach suitable for problems that deal with large deformations due to the discretization into a set of Lagrangian particles [2,3]. The particles carry the material properties, while on the grid points of the temporary background mesh the gradients are calculated. However, the classical version of MPM suffers from cell-crossing instabilities, lack of convergence, and numerical fracture, which occurs when particles move far from the cell of their original position leaving a gap of one or even more cells due to the large deformation in the simulated system [4]. The method has been improved over the last decades by various authors [5,6,7,8,9] to tackle some of its flaws, allowing MPM to find use in a wide range of applications. Therefore, we have implemented the General Interpolation Material Point (GIMP) formulation developed by Bardehagen [5] in this work since it does not

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suffer from tensile instability and has shown first-order convergence upon resolution refinement for constant particle per cell numbers even for high strain rates thus widely reducing the cell-crossing instability. The model from Johnson and Cook (JC) [4] for viscoplastic materials has been used to characterize and describe strain rate dependent phenomena, since this model is based on the local accumulation of plastic strain, while also considering the influence of temperature and pressure. This model has been widely used in industrial applications as well as micro-mechanical simulations, obtaining the required material parameters from various experimental (high-speed) setups such as compression tests [10] or Hopkinson bar tests [11,12]. When dealing with abrasive contacts at high speeds, the microstructural changes may lead to localized strain hardening, which should not be neglected since it considers the chemical composition, microstructure, and loading parameters of the system [13]. Poole et al. [14] give a thorough review of work hardening in aluminum alloys that highlights some of the most crucial factors to consider. Hence, an enormous drawback of conventional mechanical testing (with large specimens) for parametrizing material models is their investigation of “bulk” properties, while wear processes take place on the surface and may require entirely different parameter sets [15]. Abrasion tests employ a multitude of abrasive events, such as in the dry sand/rubber wheel apparatus [16]. For better control over the test conditions, scratch tests provide the possibility to set most parameters individually, such as force or scratching speed. Experimental scratch tests are usually limited to some millimeter/minute scratching speed, as specified in the standards [17,18], some test rigs extend somewhat higher, e.g., 10 mm/s [19], but they are still far from practical applications that lead to scratch damage or abrasive wear like rolling or machining. Thus, a high-speed scratch experiment is of high importance to assess abrasive wear phenomena on a fundamental level.

On the other side, the challenge from the simulation point of view is the limitation in computational power, since it only allows to model systems within a certain window of conditions. Bopp et al. [20] described in more detail some of the limits in molecular simulations and the scope covered by them in terms of time (1-1000 ps) and length (up to 10 nm) at that time. Due to fewer particles involved in the MPM method and the steady increase in resources over the last decades, this window keeps on expanding, making it possible to model more complex systems and thus narrowing the gap between experimental work and simulations. However, the use of different time integration schemes also plays a role in the usage of computational resources and the kind of system to be modelled; GIMP uses explicit integration, which is straightforward to implement, efficient, and stable for short duration dynamic problems. This leaves simulations of scratches with mm/min velocities as a challenge, because even if the use of implicit integration schemes is possible, they are also known to be computationally expensive. [21]

Material parameters at speeds relevant to tribological wear processes are important for optimizing tribosystems. As many wear systems feature some kind of surface protection, e.g., thin films, hardfacings, or in-situ formed tribolayers [22], material parameters for such near-surface regions are necessary. In this work we will prepare a toolset to gain material parameters needed for numerical simulation at application relevant speeds and tribologically interesting materials or surface layers via instrumented high-speed scratch testing aided by mesh-free modelling.

2. Methods

2.1. Material investigated

In this work, pure aluminum was chosen for investigation, as the material features extensive strain hardening behavior during plastic deformation. Further, it was well characterized in a previous paper of the authors [23], so that the material parameters necessary for the numerical simulation were previously determined. The material is standardized under EN-AW1050A (AA1050) [24], and its chemical composition is given in Table 1.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1050: EN-AW1050A (EN AW-Al99.5)</td>
<td>0.25</td>
<td>0.4</td>
<td>0.05</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05</td>
<td>Base</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Chemical composition of the alloy according [24] in wt.%
The material is produced by rolling and commonly applied in design and architecture, due to its brightening and glossy appearance. Applications requiring increased mechanical strength make use of higher-alloyed aluminum alloys. In this work, the material was cut from a 1.8 mm thick sheet metal in as-rolled condition without any further heat treatment (as is common in applications of this material). Scratching was done on samples of 70×30×1.8 mm perpendicular to the rolling direction. The initial microstructure can be seen in Figure 10 “bulk”, featuring sub-grain formation and a pronounced lattice orientation in [101] direction as typical for a rolling texture. The grain size tends to be around 6 µm in bimodal distribution with peaks around 18 µm and 4 µm.

2.2. Scratch test
As most scratch testers operate in the low velocity regime at some mm/s – which is far from the intended applications – we designed a test setup capable of scratching at speeds in the meter/second range. To achieve this, we made use of a rigid pendulum arm of ~1 m length (1.08 m and 4 kg weight) with a standard Rockwell C diamond indenter mounted on its tip. (Figure 1) This indenter has a tip radius of 200 µm on a 120° cone. Based on the geometrical situation and attached weights, the pendulum is expected to reach the estimated calculated maximum velocity of 8 m/s at its lowest point when released from the horizontal position.

The aluminum sample is placed at the bottom position of the pendulum and mounted on both sides with clamps, leaving a free area for scratching of ~40 mm. The position of the scratch can be adjusted sideways via a screw at the pendulum arm bearing so that multiple scratches are possible without the necessity to change the sample. The sample holder will also allow inductive heating for future high temperature experiments.

The length of the pendulum can be fine-tuned using a micrometer screw mounted between tip and arm (Figure 1b). Coarse adjusting of the scratch tip was done by bringing it into contact in static condition. Dynamic effects (e.g., bending of the screw and bearing clearance) then already lead to a certain penetration depth. By trial, the depth was adjusted with the micrometer screw, aiming at scratch depths within the range 10-50 µm. Several scratches were performed at each setting in order to obtain enough valid experiments within the intended range.

For the dynamic load occurring in this high-speed scratch, standard load cells are unsuitable, so a piezoelectric Acoustic Emission transducer (AE-900M-WB from NF Corporation) was used instead. It is mounted between arm and indenter, and data was acquired at 1 MHz with an acoustic emission measurement system (PCI-2 from Physical Acoustics) using an amplifier (9913 from NF Corporation). Piezo sensors are difficult to calibrate, as they react only to dynamic forces. We will use the numerical simulation of the scratches to obtain this calibration factor, as described later.

2.3. Numerical simulation
The final goal of the experiments is to obtain accurate near-surface material parameters at high speeds describing the wear behavior of the specimen. As they cannot be derived directly from the scratch response, results from numerical simulations covering a vast parameter range may be utilized to match the
experimental results. Therefore, in this work a first step is undertaken in this endeavor, with the well-known and parametrized material AA1050. Numerical simulations were carried out using mesh-free GIMP as implemented in the open-source code LAMMPS [25]. This method is well-suited for abrasive wear phenomena leading to large deformations [cf. 26,27]. We made use of the JC viscoplastic material model (Eq. 1-3), as it is well suited for plastic materials such as most metals:

\( \sigma_f(\varepsilon, \dot{\varepsilon}, T) = [A + B(\dot{\varepsilon})^n][1 + C \ln \dot{\varepsilon}^*][1 - (T^*)^m] \)  

(1)

where the normalized strain rate \( \dot{\varepsilon}^* \) and normalized temperature \( T^* \) are defined as:

\[ \dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \quad \text{and} \quad T^* = \frac{T - T_0}{T_m - T_0}, \]

(2, 3)

with the yield stress \( A \), hardening parameters \( B \) and \( n \), a strain rate parameter \( C \), a user-defined plastic strain rate \( \dot{\varepsilon}_0 \), the reference temperature \( T_0 \), and the reference melting temperature \( T_m \). As experiments are done with a diamond indenter, it was considered rigid in the simulation with Hertzian interaction. The indenter features the same geometry as in the experiments, i.e., Rockwell C shape with 200 µm tip radius. A Coulomb coefficient of friction of 0.1 was set between indenter and sample, as this proved to be representative in previous works [23,28]. For numerical efficiency and to avoid instability issues occurring at long simulation times, only the central 2 mm part of the scratch was simulated at constant depth on an aluminum block the size of 1x3x0.4 mm. To match experiments in a wide range, constant indentation depths of 20, 30, and 40 µm were simulated with a scratch length of 2 mm. The particle resolution in the MPM calculations was set to 10 µm with one particle per cell. The speed of the indenter was set to 8 m/s as calculated for the experimental scratch. The JC parameters of the aluminum block are taken from our previous work [23] and given in Table 2. A simulation snapshot of a 20 µm deep scratch is provided in Figure 2.

2.4. Evaluation

2.4.1. High-speed imaging

We used high-speed imaging to gain insight into the dynamics of the scratch process. For this, an i-Speed 727 from iX cameras was utilized, equipped with a Zeiss ZF.2 Milvus 100 mm close-up lens. The scratch setup was lit with two high-power LEDs from the MultiLed GX-8 system. The camera was oriented normal to the scratch direction, so that the entry and exit speed of the indenter can be tracked. The lens was focused on the scratch path and covers ~60 mm width (40 mm sample width +10 mm entry and exit of the indenter). 10,000 frames per second were recorded to gain clear knowledge of the dynamic behavior during the scratch experiment. At this recording speed, the camera allows a resolution of 1512×1098 pixels. The speed of the indenter was calculated during post-processing using point tracking with Xcitex ProAnalyst® software.

2.4.2. Topography evaluation

For quantitative comparison the topography of the experiments and simulations were evaluated. To this end, a topography measurement of all scratches was done with the Alicona® Infinite Focus G5 system (Figure 3 left). Afterwards, the scratches were separated and the central 2 mm selected, as this part features an approximately homogeneous depth that allows a better comparison with the numerical simulation. From this part the median profile was calculated. Of all the scratches, those most closely matching the simulated depths (20, 30, and 40 µm) were used for comparison.

<table>
<thead>
<tr>
<th>Material</th>
<th>( A ) in MPa</th>
<th>( B ) in MPa</th>
<th>( n )</th>
<th>( C )</th>
<th>( \dot{\varepsilon}_0 ) in s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1050</td>
<td>65</td>
<td>65</td>
<td>0.805</td>
<td>0.147</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2: Johnson-Cook parameters for the alloy taken from [23].
Figure 3: Topography evaluation of the high-speed scratches: multiple scratches with varying depth are produced on the sample’s surface, then individual scratches are cut out from the topography measurements and evaluated in the central 2 mm of the scratch featuring constant depth.

For the numerical scratch results, median topographic values were also calculated, discarding the beginning and the end of the scratch. Depth, pile-up, and shape of the scratch profiles are compared. The abrasive wear factor $f_{ab}$ was calculated to determine if the abrasive processes in experiment and simulation match. This factor was introduced by zum Gahr [29] giving an estimation on the dominant wear mechanism by quantifying the deformed volume on the cross-section of a scratch:

$$f_{ab} = \frac{A_g - (A_{r1} + A_{r2})}{A_g},$$

where $A_g$ is the area of the wear groove and $A_{r1}$ and $A_{r2}$ the areas of the ridges deposited on both sides of the scratch.

2.4.3. Microstructure evaluation
As scratches at such high speeds under well-controlled experimental conditions are scarcely reported, thorough microstructural investigations were performed after the experiments. In accordance with our previous work [23], cross-sections of the scratches were prepared according to a previously published routine [30] for EBSD (electron backscatter diffraction) analysis. Scannin Electron Microscopy (SEM) and EBSD were performed using a Jeol® IT 500 LV scanning electron microscope, equipped with a Bruker® XFlash 6|30 EDX-detector and a Bruker® eFlash HD electron backscatter diffraction detector. EBSD patterns were acquired at 15 kV acceleration voltage for 30 ms and analyzed via the Bruker® Esprit 2.1 software using the aluminum lattice parameter. The results are compared to the original microstructure and to speeds done at 10 mm/min and 60 mm/min on specimens as used from [23]. As region of interest, an area of 130x70 µm directly beneath the scratch surface was chosen. Evaluations on the inverse pole figure (IPF) plots and the concomitant simultaneous grain orientation change as well as the grain average misorientation (GAM -- reflects the grains deformation state) of the first 50 µm depth were performed to discuss the occurring mechanisms.

2.4.4. Force evaluation
A piezoelectric force sensor was placed between the indenter and the swing arm. The force was evaluated by treating the signal obtained directly from the readings of the piezo sensor with 1 MHz acquisition rate. The dynamic impact causes oscillations in the force signal, hence absolute values, e.g., corresponding to the maximal force, will be inaccurate. The computation of the cumulative integral of the piezo signal would provide an estimate of the work needed to produce a scratch in the sample. Figure 4 gives an example of the evaluated force signal of a 25 µm deep scratch. A linear trend in the energy dissipation across the whole length of the scratch can be observed. Depending on the scratch depth, a different scratch length is entailed. This leads to both longer force signals and steeper increase of the signal when the scratch is deeper. To directly compare the signal to the numerical simulations, the central 2 mm of the scratch are located, and the energy needed for deformation in this area is computed.
3. Results

3.1. Contact area

The numerical simulations provide a vast insight into the deformation process caused by the abrasive scratch event. Various evaluations are possible on the numerical results, including stress distributions, occurring strains and strain rates [9] or geometrical information gained directly at the contact, which is in contrast to the remaining plastic deformation which can be observed after the experiment. Most of these parameters are not directly accessible in the experiments and accurate numerical simulations are needed thereto. We have chosen here one example, namely the real contact area with the indenter, which is the key for calculating the scratch hardness. Figure 5 shows the real contact area between the indenter and the sample at different positions along the scratch. Particles in red are lifted above the original surface, while the color at the bottom represents the set scratch depth of 20 and 40 µm, respectively. It is clearly visibly that a large burr is formed in front of the indenter getting moved till the end of the scratch. This of course is favored by the soft nature of the investigated aluminum.

For calculating the hardness, the applied force is divided by the projected contact area. In case of scratch hardness, the projected contact area is assumed to be the half circle of the leading edge of the indenter inserted in the remaining plastic deformed width measured after the experiment. Figure 5 shows that the elastic behavior of the material greatly enlarges the real contact area during scratching, e.g. the elastic proportion encloses large parts of the indenter even behind the leading half of the indenter. Table 3 gives a direct comparison of the assumed contact area.

![Figure 4](image1.png)

**Figure 4:** Cumulative integration of the signal obtained from the piezo sensor: the central 2 mm are selected and the signal in this area integrated.

![Figure 5](image2.png)

**Figure 5:** Real contact area between the indenter and the aluminum block and height information of the particles in contact at a) 20 µm and b) 40 µm scratch depth. Scratch direction is from left to right.

<table>
<thead>
<tr>
<th>Set scratch depth in µm</th>
<th>Entailed scratch width in µm</th>
<th>Assumed contact area in mm²</th>
<th>Simulated real contact area in mm²</th>
<th>Deviation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>24.7</td>
<td>0.025</td>
<td>0.048</td>
<td>1.94</td>
</tr>
<tr>
<td>30</td>
<td>34.6</td>
<td>0.035</td>
<td>0.070</td>
<td>2.02</td>
</tr>
<tr>
<td>40</td>
<td>46.4</td>
<td>0.046</td>
<td>0.092</td>
<td>1.98</td>
</tr>
</tbody>
</table>

Table 3: Comparison of contact area according to the half-circle assumption with real contact area as calculated with the numerical simulations.
3.2. Scratch profiles

In this and the next chapters we will concentrate on data we can directly compare between experiment and simulation. First, typical experimental scratch profiles are compared to the simulated ones. Simulations were done at 20, 30, and 40 µm, while the experiments cover a range of 10-50 µm. Three experimental scratches lying close to the simulated depths are displayed in Figure 6.

The scratch depths and corresponding pile-up heights are very well comparable for the scratches shown. The experimental ones are slightly asymmetric, with the right pile-up being smaller than the left one, most probably due to slight misalignments during mounting of the samples. The most prominent difference is the shape of the groove. Although simulations and experiments make use of the same indenter shape, the experiments result in a pointier groove than the simulations, i.e., elastic recovery pushes the sides of the experimental scratch back into the groove more than the tip.

For quantifying the profile data of scratch tests, the abrasive wear factor \( f_{ab} \) was established by zum Gahr [29], setting the displaced area at the sides (ridges) in relation with the scratch area according to Eq. 4. Ideal cutting leads to \( f_{ab} = 1 \) (no ridges due to material removal); ideal plowing results in \( f_{ab} = 0 \) (material from the groove is entirely deposited in the ridges). For ductile materials such as the aluminum investigated here, very low values of \( f_{ab} \) are expected (low yield stress to Young’s modulus \( A/E \) ratio in the range of \( 10^{-3} \), see Figure 7a) [27]: those results were obtained with 25 µm scratch depth at 100 m/s without strain rate dependence (\( C=0 \)).

Interestingly, the simulation (squares in Figure 7b) showed a sharp increase in \( f_{ab} \) with increasing depth from ~0 at 20 µm depth to ~0.3 at 40 µm depth, i.e., with increased deformed...
volume, the characteristic of the wear process transitions from pure plowing towards cutting. More deformed volume leads to higher strains and higher strain rates in the material, leading to an increase in the yield stress due to viscoplastic effects. This also seems to entail an increasing amount of cutting in the wear process. To see if this change in wear mechanism is also reflected in the real system, $f_{ab}$ was also calculated for the experimental scratches (circles in Figure 7b).

As the exact simulated scratch depths were not achieved experimentally, there are some slight deviations in depth for the given examples, but clearly the experimentally observed $f_{ab}$ also rises with increasing scratch depth, thus, following the trend observed in the simulations. The deviation from the simulated values becomes somewhat larger with increasing depths, which may be due to an overestimation of the strain rate parameter $C$ in the simulation. In general, an abrasive wear factor larger than zero indicates the formation of wear particles. Although no debris was readily visible in the vicinity of the scratch, we acquired high-speed images for verification.

3.3. High-speed imaging
In order to gain insight into the wear event and energy uptake (reduction of pendulum speed) of a high-speed scratch, we recorded shots with the high-speed camera at 10,000 fps for selected scratches. This acquisition rate allows a resolution of 1512×1098 pixels, showing the expected wear particles in case they are formed. In the supplementary material (Video 1), a high-speed shot of a ~30 µm deep scratch can be viewed, reduced in speed by a factor of 400. The indenter enters from the right and exits to the left. Via point tracking, the entry and exit speed were measured to be $v_{\text{entry}}=6.8$ m/s and $v_{\text{exit}}=6.5$ m/s. It therefore deviates slightly from the 8 m/s calculated according to the measures and mass of the pendulum. The scratch event, i.e., the plastic deformation of the scratched area, required 8 J of energy in this case.

The most important contribution of the high-speed videos was the visualization of wear particles. Due to the high resolution and frame rate the camera can achieve, some wear particles trailing the passing indenter can be clearly seen. One frame is shown in Figure 8, where the scratch is produced from right to left, reflecting light in the bottom part of the image. Blurred due to the high speed, the indenter can be seen on the left, shortly before exiting the sample. Some small wear particles are visible trailing the indenter. Their sizes are in the range of some 10 µm, and they are also traveling fast, leading to the blurred tail in the image. At the indenter position shown in Figure 8, some 5 particles can be counted. Shortly afterwards, when the indenter has left the sample, this number increases to ~15 as visible in the supplementary Video 1. By the observed formation of these wear particles, we could directly confirm that $f_{ab}$ should be significantly higher than 0.

![Figure 8: One representative frame of a high-speed video showing a ~30 µm deep scratch event performed at ~6.8 m/s. The full video can be accessed via the supplementary material Video 1.](image)

3.4. Force results
The evaluation of the data obtained from the piezo sensor for various scratch depths was performed as described in section 2.4.4, and the results for three selected scratches (closely matching the simulated ones) are displayed in Figure 9. Depending on the scratch depth, different scratch lengths are produced due to the pivoting movement. Note that the scratches are shallower than expected from their length according to the radius of motion (swing arm length), i.e., the arm is pushed upward or the sample downward during scratching – as the entire setup is not perfectly rigid, this cannot be avoided. Although this complicates the setting of a defined depth, it has no detrimental effect on the results and evaluations, as they concentrate on the central two millimeters featuring an almost constant – and exactly measured – depth.

Comparing the three measured scratches in Figure 9a, the different slopes are the most important outcome. The deeper the scratch, the steeper the gradient of the piezo signal. After an initially shallower slope of the two deeper scratches, a linear signal can be seen until the end of the scratch. For the 25 µm scratch, there is no kink in the curve, and it features a constant slope right from the start.
After locating the central two millimeters of the scratch, the integral was calculated within these borders and plotted against the scratch depth in Figure 9b. The so acquired results showed a linear trend with increasing scratch depth within the investigated range of ~25-45 µm depth. Therefore, the work required for the deformation during scratching increases linearly (as does the groove area $A_g$) within this small range of scratch depths. With much shallower scratches, the trend might diverge from the linear one found here, i.e., for future use of scratch experiments in material characterization, one must be aware of the optimal depth range.

### 3.5. Microstructure evolution

Microstructural changes during scratches were visualized via EBSD measurements as described previously. A comparison of different scratch velocities is done with low-speed scratches obtained in a previous study [23]. The graphical summary of the obtained results is presented in Figure 10. In the inverse pole figure (IPF) plots, clear differences can be seen when comparing the microstructural changes in the deformed zones. Here, the strain rate as represented by the scratch velocity has a clear influence. The initial microstructure exhibits grains elongated in rolling direction with distinct sub-grain formation at a grain tilting angle of around 45° ([111] to [001]).

At low speed (10 mm/min), a deformed zone of 25 µm thickness can be identified, characterized by grain refinement as visible in the IPF plot. In the near-surface zone, the misorientation remains at a low level <5° grain average misorientation (GAM), which indicates dynamic recrystallization [31,32]. Nevertheless, a certain deformation as well as residual stresses [cf. 33] remain in larger depths as indicated by the GAM of ~10°. Higher speeds (here, 60mm/min), lead to thinner grain-refined zones (<15 µm), but a deeper extent of residual stresses represented by GAM. With the new scratches at highest speed (6.8 m/s – 6,800x faster), the lowest extent of ~6 µm of the grain-refined zone can be identified via the IPF plots. The highest GAM in the zone directly beneath the dynamically recrystallized zone can be seen in this specimen. In some areas, more than 20° GAM were measured, confirming the conclusion that a higher relative velocity leads to reduced deformed zones, but a higher extent of strain hardening as indicated in previously performed studies via scratch tests [34] as well as during abrasive processes [35].

### 4. Discussion

In this work, we achieve experimental scratch testing velocities beyond 1 m/s, which are of high importance for many industrial applications, e.g., rolling of aluminum [23], where a glossy and scratch-free surface is essential. Several previous studies by the authors [9,23,26,27] had the drawback of a gap between experimental scratch speeds and numerical simulations of the scratch. This gap covered several orders of magnitude and resulted in abrasive wear factors $f_{ab}$ showing opposing trends in simulation and experiment (Figure 11, taken from [23]). Hence, it could not be proven so far, if the simulations correctly represent reality in a single abrasive wear event. In this study, we managed to close this gap by obtaining scratch data at high speeds.
Figure 10: Deformation caused by scratch experiments at different speeds as seen on cross-sections: the central region of the scratch profile (deepest position) is shown. Inverse pole figure plots and grain average misorientation plots as obtained via electron backscatter diffraction. Scratch direction is into the plane.

Figure 11: Literature data comparing experiment (≤0.001 m/s) and simulation (≥1.0 m/s) for AA1050: abrasive wear factor $f_{ab}$ as published in [23]: a gap of ~4 orders of magnitude is gaping between standard scratch experiments and numerically manageable speeds.

The scratch simulations very closely resemble the experimental scratches with respect to topography. Derived parameters, in our case the abrasive wear factor $f_{ab}$, showed an excellent agreement (Figure 7b) and validate our simulations with the chosen JC material model. The ultimate goal is to obtain material parameters for the JC material model with simple means of scratch testing. This has several advantages: i) sample preparation is much easier: merely a flat, polished surface is required; ii) expensive equipment like a (high-speed) tensile or compression test is not needed; iii) material parameters can be detected locally, e.g., within a thin surface zone, while other methods require bulk (volume) samples. We see the main advantage in this third point, as many (wear protection) materials and regions of interest cannot be prepared for tensile/compression testing, e.g., thin films, coatings, hardfacing, tribologically affected surface zones by severe plastic deformation, etc. Hence, material parameters for such materials and regions are not accessible so far, but would be necessary for correct modelling of tribological interactions and further component optimization.

The workflow for determining the JC parameters $A$, $B$, and $n$ from scratch results is presented in [36]. The basis for this endeavor is a database of simulated scratches of a large
matrix of material parameter combinations. After an instrumented experimental scratch, topography and force data can then be compared with simulated results, and the underlying material parameters found. Unfortunately, single scratches (one load/depth) and the sole topography of the resulting scratch do not allow an unambiguous distinction of the JC parameter set. Therefore, more than one depth is needed, as well as an instrumented scratch, i.e., knowledge of the force required for deformation. This poses a challenge for high-speed scratch experiments, as high-speed force sensors on piezo-basis are difficult to calibrate. The indirect measure for the force presented in Figure 9b seems sufficiently stable, even considering the oscillations caused by the high-speed impact of the indenter. For the investigated scratch depths, Figure 12 gives a correlation of the tangential force as calculated in the simulation with the measured piezo signal. Both results follow a linear trend in the investigated range, differing only in a constant coefficient of $10^{9}$. Knowing this linear relationship, direct measurements of the force needed for deformation during scratching are now possible.

![Figure 12: Correlation of simulated force data with experimentally measured piezo-sensor data obtained for the high-speed scratches. Note the different ordinate axes for simulation (left) and experiment (right).](image)

With this toolset, unknown materials can now be classified, and the JC parameters derived from “simple” scratch experiments. This provides an enormous advantage over classical material parameter determination via uniaxial bulk-material tests, i.e., the parameters in the tribologically interesting zone can be assessed. Further, we intend to extend the work presented in Ref. [36] by taking the next term of the JC material model into account, namely the strain rate dependence, by combining low-speed with high-speed experiments.

5. Conclusions

With a combination of numerical simulations and experimental high-speed scratch experiments, a tool set for identifying parameters for the Johnson Cook viscoplastic material model is presented, allowing a close-to-application assessment at speeds relevant for high-speed industrial applications. The following main conclusions can be drawn:

- High-speed scratch experiments at >6 m/s were achieved with a pendulum-type setup. The scratches were performed in a depth-controlled mode, and a measure for the tangential force is acquired via a piezoelectric sensor.
- The topographies of the experimental and numerical scratches are in very good agreement.
- The corresponding abrasive wear factors are also in good agreement. Interestingly, they rise with increasing scratch depth, i.e., the cutting mode of the abrasive process increasingly dominates with increasing strain and strain rates. High-speed imaging has proven the formation of wear particles and thus the cutting component of the wear process.
- An integral value of the tangential force matches the simulated forces, thus providing a calibration factor for the piezoelectric force sensor.

With this methodology, scratch experiments with unknown materials can now be used to parametrize the Johnson-Cook material model. This is especially important for layers or tribologically affected zones, where standard mechanical testing is not possible. For the method presented here, only a flat surface of the material to be tested is necessary, which constitutes an invaluable advantage over conventional mechanical testing.

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7. Competing Interests
The authors have no relevant financial or non-financial interests to disclose.

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8. Supplementary material
Video 1: High-speed video of the scratch experiment taken with 10,000 frames per second. Note the wear particles trailing the indenter when reaching the end of the scratch.
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