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Cutting of highly plastic clay: analysis of large rapid deformation processes

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ABSTRACT: Clay is a notoriously challenging material to dredge. Due to its adhesion and plastic behaviour, it may clog the suction head and/or clay balls could form in the pipeline. This will raise difficulties in estimating the production, the required power and increase the risk of downtime. As this is an expensive risk for the dredging industry, the cutting process requires in depth research to achieve better understanding of the process, to prevent problems and to mitigate risks.
Available literature on clay deformation and soil cutting has been reviewed. Important topics for the cutting process are the interaction between the clay sliding over the blade and the resulting macro deformation of the chip. Various cutting regimes can be distinguished, including the: Flow regime, Tear regime, Curling regime, etc. Additionally the best practices for soil bin experiments have been included.
Review of the available literature and analysis of published models is used to design a soil bin experiment dedicated to test the process under conditions relevant for the dredging industry. The objective of the CHiPS project is to study cutting regime transitions for dimensionless parameter groups of soil properties and operating conditions. Transitions range from static traction problems on soft mud to grinding action on stiff clay.
Preliminary results and analysis of these clay cutting experiments are presented. The test rig developed for the CHiPS project is functionally performing satisfactorily, but requires a stronger drive to test high-strength soils.
Keywords: Clay cutting, Plasticity, Adhesion/cohesion ratio, Deformation types, Chip formation

1 INTRODUCTION

Dredging is the activity of removing submerged sediment and depositing it to a designated area. A common tool for this is a Cutter Suction Dredge. This dredge has a rotating cutter head with teeth for excavation of the sediment. The sediment is mixed with the surrounding water and sucked into the dredge pump for further transport down a discharge pipe to the deposition area.

Whenever clay is encountered in a dredging project, it may cause several problems for the operator of the dredging equipment. A high shear strength for dredging is in the range of 50-200 kPa (CEDA/IADC, 2018). Consequently, the required power to remove it will be high, or conversely, the production will be reduced. Or another issue, assuming no internal friction and the clay exhibits a high plasticity and adhesion also in the same range of the tensile strength, the clay will stick to the equipment. The clay will not release from the blade and be drawn into the suction mouth and completely cover the cutter head (see Figure 1).

Figure 1 Clogged cutter head in highly plastic clay

Furthermore, when the plasticity is high and there is sufficient sand content, the broken chunks of clay may form clay balls that roll down the pipeline and block it eventually (Hoff and Kolff, 2012). The underlying processes, which cause these problems, are related to the actual cutting of the clay. The cutting process in dredging is characterised by large rapid plastic deformation under rapidly changing conditions. An experiment has to be designed to test the ideas of the cutting models available (Miedema, 1992)

Additional experiments have to be designed for the transport of the chip over the tool and the release of the chip into the suction mouth. These factors are related to clay plasticity and mineralogy and their influence on the deformation along the concerned interfaces of this chip. Both theoretical and experimental research has been carried out on the deformation process. More literature is available on deformation of metals and plastics, less so on the deformation of clay during cutting.

Plastic deformation is a non-reversible process in response to applied forces. During the process, the internal structure of the material is changed, and the object transforms to a new overall shape. The examined literature is mainly investigating this rapid plastic deformation for tillage in agriculture, collapse of retaining walls or even machining in metal working. The cutting process in dredging is characterised by large rapid plastic deformation. The conditions change rapidly for a single stroke. Cutting speed: 0.1 m/s-2 m/s and cutting depth: 0.005 m-1.5 m. (Winkelman et al., 2024) These dynamic conditions result in various cutting regimes succeeding each other.

A solid validation of the models proposed by (Miedema, 1992): flow model, shear model and tear model, for cutting in clay in dredging is hard to find. A suitable experiment has to be designed to test the ideas of the models most widely used in the dredging industry, (Winkelman et al., 2024). A linear cutting test with an inclined blade through a 2D geometry is a configuration that is easy to model and analyse, (Hatamura and Chijiiwa, 1975). A similar approach is followed with these objectives for the design of the experiment:

- Identifying the main parameters influencing the cutting forces and the cutting regime
- Designing general arrangement for testing linear cutting models
- Capture the signals for force and deformation

The resulting design is presented here in this paper and preliminary initial results from the commissioning phase are discussed. Future work includes validation with modern strain rate models and relation to advanced numerical model.

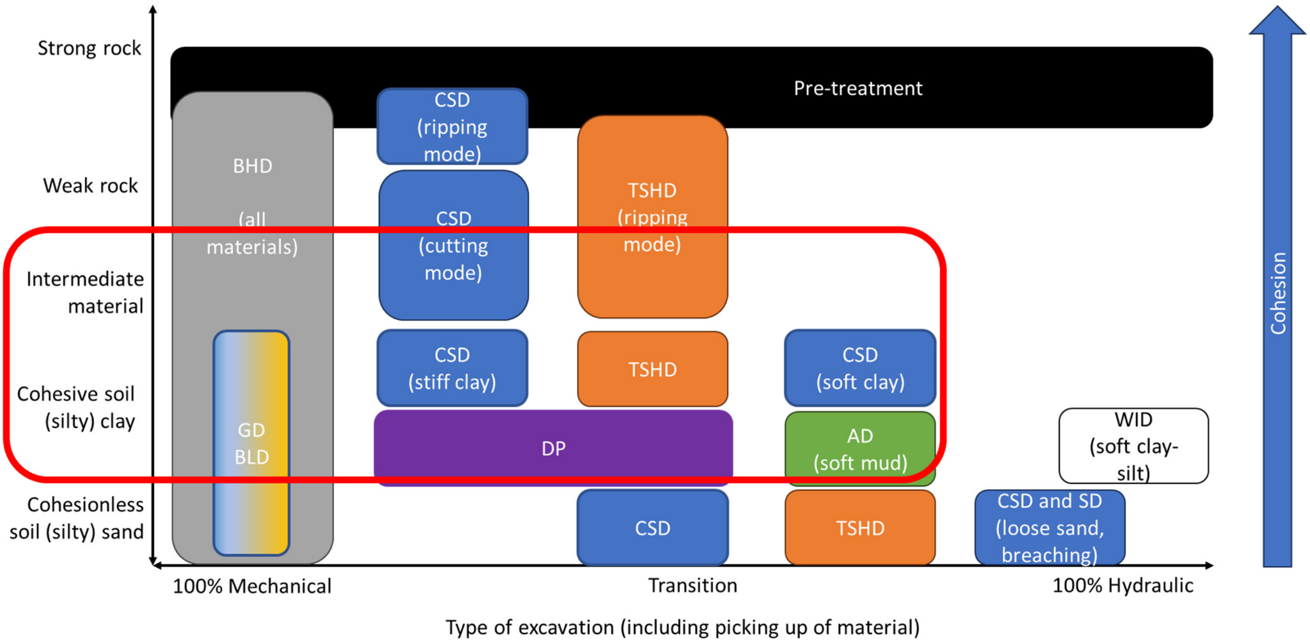

Figure 2 Dredging equipment and their applications (Based on PIANC 2016)

BACKGROUND

Practically, there is a guideline (see Figure 2) what dredging equipment to use for which soil, (PIANC, 2016). The distribution of the dredge types over the mechanical/hydraulic scale, depends on the energy required to put into a dredging project and still make a viable business case. The soil condition is characterised into different categories in relation to the cohesion, no qualitive division is provided. Additionally, more parameters are involved in the cutting process.

The equipment highlighted in the red box in Figure 2 is most likely to be employed in cohesive and intermediate material. As they have a certain degree of mechanical interaction with the material to be excavated, the encountered cutting processes are of most interest for this research, as it aims to provide a theoretical basis for the recommendations to use this equipment for this soil.

The equipment indicated is: AD: Auger Dredge, BHD: Back Hoe Dredge, BLD: Bucket Ladder Dredge CSD: Cutter Suction Dredge, DP: Dredge Ploughs, GD: Grab Dredge, PSD: Plain Suction Dredge, TSHD: Trailing Suction Hopper Dredge, WID: Water Injection Dredge.

2 PHYSICAL PHENOMENA

Although the cutting process in a dredging environment is a three dimensional process, it is easier to construct a two dimensional model and design an experiment accordingly. As the teeth used for clay are relatively wide, the error on the side is relatively minor. Also, most dredging applications are involving rotary cutting devices, but a linear model and experiment is used as simplification, as the cutter head radius to the cutting depth is very large. The blade used in the experiments is of similar dimensions as the prototype cutting teeth used for clay.

2.1 Deformation mechanisms

The deformation of the clay depends on the conditions during cutting. Several deformation mechanisms have been observed. Usually, multiple shear planes can be identified, either continuous or discontinuous (Hatamura and Chijiiwa, 1975), (Dewhurst and Collins, 1973), (Schoonbeek et al., 2006), although for simplification, a single shear plane is often assumed (Miedema, 1992). An array of shear lines could be modelled with the slip-lines-method (Dewhurst and Collins, 1973) proposed by (Schoonbeek et al., 2006). For calculating the total deformation force on the object, the shear stress along the shear lines must be integrated in magnitude and orientation over the area defined by the length of the shear line and the unit width. This shear stress depends on the shear rate along the shear line. Solving the integration determines the geometry and the rate at which the deformation is happening and consequently the deformation mechanism.

2.2 Chip formation types

The involved forces on the chip are identified (see Figure 3). The tugging force at the end of the chip is usually not included in the models. The others usually are included.

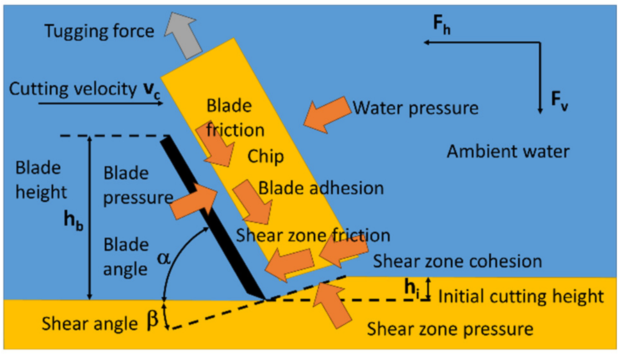

Figure 3 Cutting forces on a clay chip

Depending on the combination and ratios of the forces, chip may have a different chip formation type. Identified clay cutting types are: flow type, shear type, curling type and tear type. Cutting regimes in non-clay materials which may also apply to clay soils include: serrated, chaotic and build-up-edge; these are discussed in literature, but not specifically in the context of clay soils. Mostly, they can be classified as continuous (i.e. uninterrupted material removal with smooth cut surface), and discontinuous (distinct, separate, rough and irregular cut surface). The cutting type is also depending on the deformation mechanism (e.g. plastic flow, shear, brittle fracture, complex, etc.). However, for clay cutting, the relation between the cutting types and deformation patterns is not always known. The rapid deformation changes will cause the clay to retain characteristics of the previous deformation as in cyclic loading (O'Laughlin et al., 2020)

2.3 Parameter group evaluation

The traditional method of characterizing the deformation mechanism and derive the cutting type is the deformation rate. This is the ratio of the cutting velocity to the cutting depth. This is also illustrated by the published experiment results, that seem to cover the whole range of the deformation rate in dredging conditions (see Figure 4). The data points are covering selected tools, teeth dimensions and soil composition.

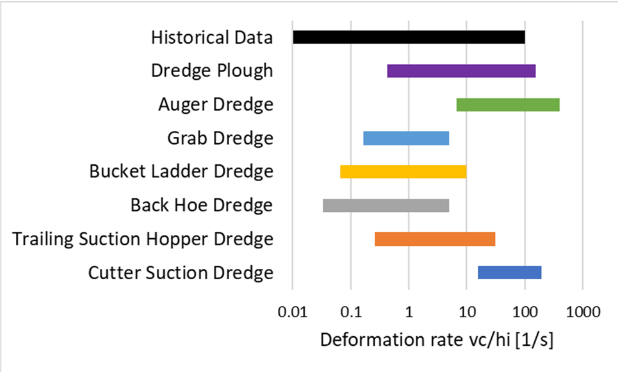

Figure 4 Operating range and published data expressed in deformation rate (Winkelman et al., 2024).

Another approach is to characterise the cutting process with dimensionless parameter groups (Winkelman et.al., 2024). The most interesting ones, with the most available published data are the Shear rate group and the Blade contact ratio.

$$\textit{Shear rate group}: \frac{c}{\rho v_c^2} \quad (1)$$

$$\textit{Blade contact ratio}: \frac{L}{h_i} \quad (2)$$

With the clay density ρ (kg/m^3), cohesion c (Pa) and cutting velocity v_c (m/s), contact length L (m) of clay to the blade and cutting depth h_i (m). Apparently, there is no historical literature data for a combination of high values in both groups.

3 EXPERIMENTAL SETUP

3.1 Test rig design

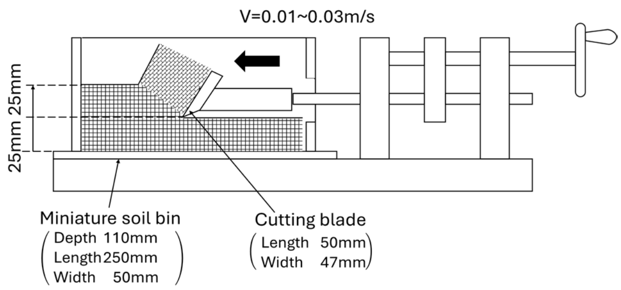

Figure 5 Apparatus for investigating the deformation of soil by cutting (from Hatamura and Chijiiwa, 1975)

There is a relatively well documented set of experiments (Hatamura and Chijiiwa, 1975). The dimensions of the soil box and blade are close to the relevant teeth on the cutter head, so their design seems quite well suited for investigating the cutting conditions in dredging (see Figure 5). This setup was the inspiration to execute this with modern technology, using an electric drive, digital signal processing and video recording (See Figure 6).

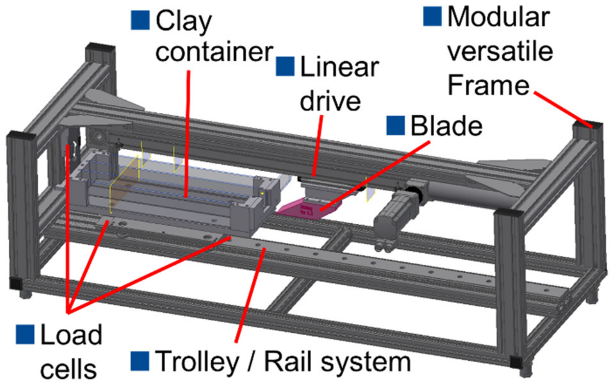

Figure 6 General arrangement of the test rig

The material chosen for investigation in this case was an artificial clay: Bisbal Ceram, Pastart, White Modelling Clay, to get consistent results. By varying the water content, the cohesion and adhesion were adjusted as needed for the test matrix. Later research can be done on natural marine clays as mentioned by (Lunne et al, 2011). In addition to the original setup, there was an option to test with the cutting process submerged. The blade is attached to an exchangeable carrier block, driven by a linear electric motor. The blade is sharp. Worn blades are to be expected, but not as relevant for dredging clay as for other dredging operations (Verhoef, 1997). The cutting forces are transferred through the container on rails to one horizontal load cell and two vertical load cells. The force signals were captured into .csv files. Further processing of the three signals enabled the calculation of forces on the blade-clay interface: horizontal force, vertical force and moment. Two cameras were attached, one static on the frame and one mounted on the carrier block, moving with the blade. To facilitate the automated image processing, a 5x5 mm grid was printed on the side of the clay block (see Figure 7).

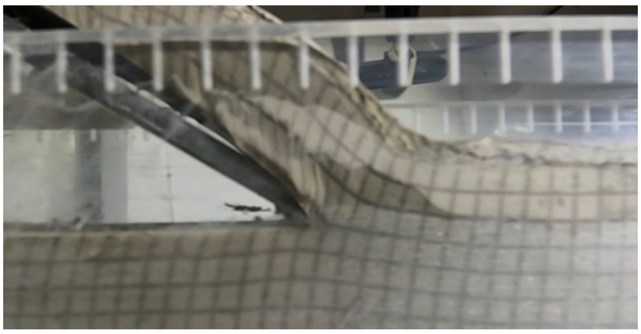

Figure 7 Side view of clay block with printed grid

The subsequent image processing was performed with PIVlab version 3.02. Outputs of the image processing were the chip thickness, the shear angle and the strain rate (see Figure 8).

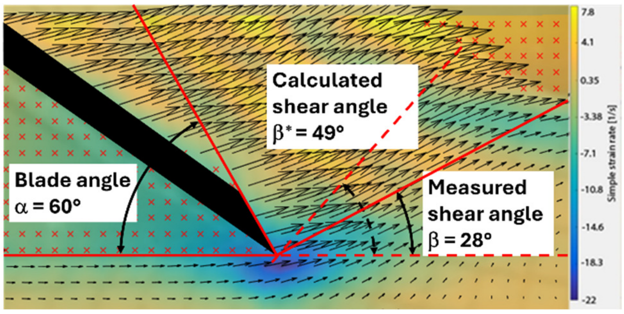

Figure 8 PIVlab results for shear angle test

3.2 Test matrix

Based on the parameter evaluation in Section 2.3, the most interesting set of parameters (Shear rate and blade contact length) to investigate was to have a range of settings for Cohesion (30-60 kPa), Adhesion (1-7 kPa), Blade material (Steel and Lexan), Blade angle (15-75 degree), Blade length (0.01-0.15 m), Cutting velocity (0.1-0.5 m/s) and Cutting depth (0.0075-0.02 m). From all the combinations, 30 were selected to investigate the behaviour of the material during cutting. The test cases were selected to simulate the high-speed and deep-cutting conditions expected in dredging. The results from these combinations are still under investigation.

For measuring the cohesion and the adhesion of the clay, a direct shear box was used. The cohesion was measured by shearing under different stress conditions and finding the intersection with the shear stress axis. The box was also modified to shear against the blade material, resulting in the adhesion for the zero normal stress condition. The difference between the adhesion of steel (12.5 kPa) and Lexan (2.4 kPa) was significant. Remarkably, the internal friction angle was 4°, but not zero. The assumption by (Miedema, 1992) is that than the external friction angle can be neglected also. However, the adhesion tests resulted in a non-negligible external friction angle (see Figure 9). The external friction angle for steel (11.47°) and Lexan (13.7°) did not differ significantly.

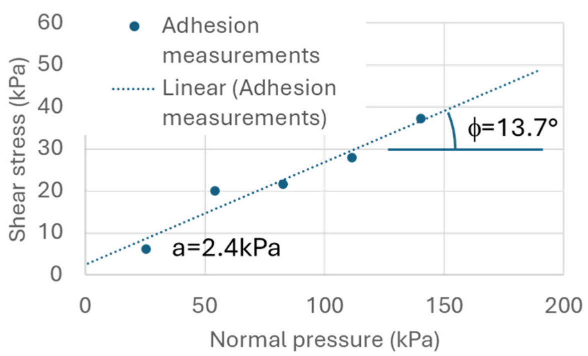

Figure 9 Measuring the external friction angle from a modified direct shear test on a Lexan blade

Another observation from the cohesion tests, was that the assumption that the tensile strength is in the same order as the cohesion does not always hold. For measuring the tensile strength, the rig was also modified to do a direct tensile test. This was explored for cohesion even outside the test matrix (see Figure 10).

The values for the tensile strength were recorded together with the results for the cohesion and adhesion, but were not used as a setting in the test matrix.

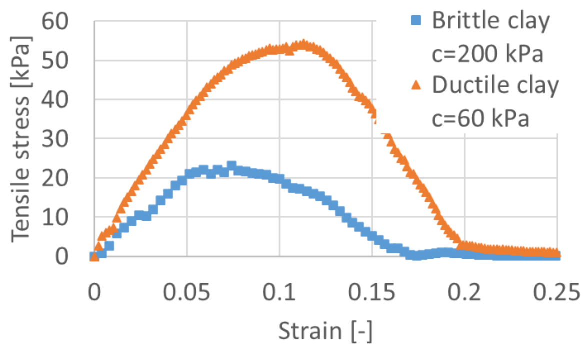

Figure 10 Direct tensile strength test

4 PRELIMINARY RESULTS

Out of the 30 tests conducted, 5 were unsuccessful because the required cutting force at higher speeds and greater cutting depths exceeded the predictions made by the models used to specify the drive. As the cohesion, adhesion and the cutting depth were difficult to set in advance, they were measured once the clay samples were prepared and cut. Although the setting was difficult, the measurement of these parameters had a low spread and a high reliability, they were taken as accurate.

4.1 Repeatability

For some tests, the resulting settings were very close and did not contribute to the variation of the parameters, but instead were used to verify the repeatability of the test procedure. Tests 4 and 5 had a cohesion of 60.8 kPa and 58.1 kPa, an adhesion of 6.7 kPa, 60 degree blade angle and 0.011 m blade length and ran at 0.3 m/s. The measured cutting depth turned out to be 0.03 m and 0.033 m. The resulting force signals are almost identical (see Figure 11).

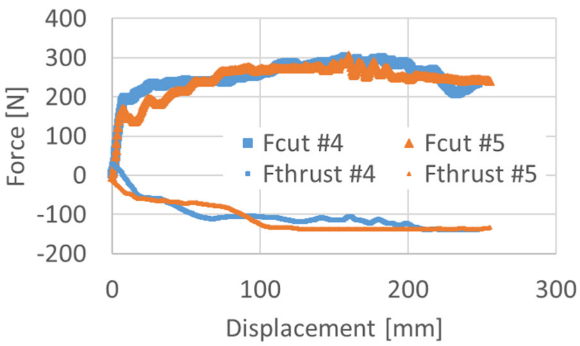

Figure 11 Repeatable results from tests 4 and 5

4.2 Cutting depth variation

As an example of the workflow, the cutting depth was varied. The steady middle section of the recording was used for further analysis. The force signals were averaged and had the deviation determined (see Figure 12).

The results for the cutting depth can be further checked in the blade length parameter group. Other parameters will be investigated similarly.

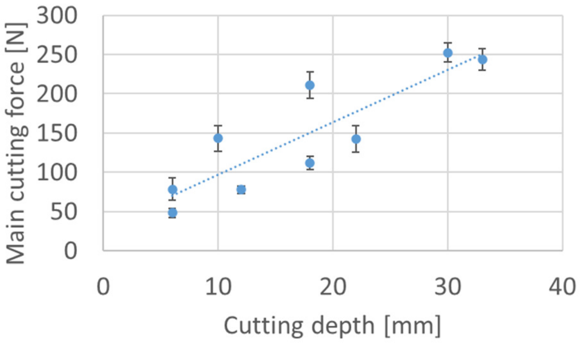

Figure 12 Approximate linear relation between cutting depth and cutting force

5 DISCUSSION

The internal friction angle in this case was non zero, but so small it could be neglected in these tests. But it also indicates, that it is there and can have an influence on the resulting cutting forces. The external friction force can not be neglected, as it is substantial. In this clay, it was in the order of 13°. It still has to be analysed whether this unexpected extra force did contribute to the higher cutting forces experienced and not predicted by the model by (Miedema, 1992).

Working out the cohesion and adhesion with the Mohr's Circle methods, it was observed, that the tensile strength is not always of the same order as the cohesion. As seen in the tensile strength for a cohesion of 60 kPa is ca. 54 kPa. However for a cohesion of 200 kPa it is only ca. 23 kPa. Thus, the brittle clay behaves more like soft rock, due to the loose structuring of the clay. This can significantly change the moment the chip breaks on the blade and what the contact length will be. This will result in a tear type cutting regime. In this case the cohesion is too high for the drive to execute such tests.

The used flow model of (Miedema, 1992) does assume that the adhesion is in a fixed ratio to the cohesion, however the measurements indicate that there can be a broad range for this ratio depending on the water content of the clay and the surface properties of the blade. The relation to water content and pore pressures on the stresses as mentioned by (Zhang et al, 2018) can be investigated.

The design of the setup was inspired on the system employed by (Hatamura and Chijiiwa, 1975). The specifications for drive and test matrix were based on the model by (Miedema, 1992). This turned out to be a challenge to test for high cutting velocities and high cutting depths due to drive limitations of the test rig. The flexibility and repeatability are good. The data is consistent and ready for further analysis.

By printing a grid on the side of the clay, the PIVlab software package highly effective at capturing the chip thickness, the shear angle and the strain rate.

6 CONCLUSIONS

Overall, the setup satisfies the objectives of the research and in this case the objectives for the design have been met, though missing on the performance of the drive, which will be improved in the next phase of the CHiPS research project.

Next to the expected parameters used in the available models, the adhesion has to be measured, a fixed ratio can not be trusted. And the internal and especially the external friction are to be taken into account for improving the clay cutting models. The tensile strength is also a property to measure and implement in an improved model.

The Hatamura and Chijiiwa inspired test setup is sufficient, but needs improvement in the specifications for the drive. The drive can be updated after improving the cutting models, taking into account the above mentioned extra parameters.

The combination of a printed grid on the side of the clay and evaluation with PIVlab works well to capture the chip thickness, the shear angle and strain rate.

The collected data is clean and reliable, it can be further analysed for validation of the models.

Further research will include modern strain model rate validation and comparing with advanced numerical simulations.

AUTHOR CONTRIBUTION STATEMENT

M.O. Winkelman: Conceptualization, Data curation, Formal Analysis, Writing,- Original draft. **F.T. Kruis**: Data Curation, Investigation, Methodology. **D.L. Schott**: Supervision, Writing- Reviewing and Editing. **R.L.J. Helmons**: Supervision, Writing- Reviewing and Editing.

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