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GREEN-LOOP

Sustainable manufacture systems towards novel bio-based materials

WP5 – Wood composites material production

D5.5 – Wood composite properties from tribological evaluation

Document information

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GREEN-LOOP Consortium Partners

	Partner	Acronym	Country
1	IDENER RESEARCH & DEVELOPMENT	IDE	ES
2	NATIONAL INSTITUTE OF CHEMISTRY	NIC	SI
3	SLOVENIAN NATIONAL BUILDING AND CIVIL E. I.	ZAG	SI
4	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	FHF	DE
5	LABRENTA SRL	LBRT	IT
6	MIXCYCLING SRL	MYX	IT
7	NERO SU BIANCO	NSB	IT
8	TERRE DI ZOE'	TDZ	IT
9	IRIS TECHNOLOGY SOLUTIONS, SOCIEDAD LIMITADA	IRIS	ES
10	GLOWNY INSTYTUT GORNICTWA	GIG	PL
11	AACHEN UNIVERISTY: PROCESS CONTROL ENGINEERING / AACHEN UNIVERISTY: INSTITUTE OF SOCIOLOGY	AAU	DE
12	AUSTRIAN STANDARDS INTERNATIONAL	ASI	AT
13	INSTITUTO DE SOLDADURA E QUALIDADE	ISQ	PT
14	AXIA INNOVATION UG	AXIA	DE
15	ASOCIACIÓN DE INVESTIGACIÓN METALÚRGICA DEL NOROESTE	AIMEN	ES
16	NATIONAL COMPOSITE CENTER	NCC	UK
17	UNIVERSITY OF BRISTOL	UBRIS	UK

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Executive Summary

This deliverable entitled D5.5 - Report of Wood Composite Bearings (WCB) properties from tribological evaluation for tooling adaptation (injection unit) is the result of task T5.5 as well as related tasks in WP5. In this rather early stage of the project, particular relevance is given to Task 5.1, in which requirements and specifications for WC bearings have been defined. The results of T5.1 were reported in D5.1 *Wood composites materials specifications definition* which was submitted within the GREEN-LOOP project at the end of month 4 of the project [M01-M04].

In a recent Deliverable (D5.1) an overview of the final products expected from the wood composites value chain in terms of performance and technical characteristics as described in the GREEN-LOOP Project was provided. LBRT, as on representative end user, will test wood sliding bearings supplied by FHF in a relevant environment.

To develop these prototypes, suitable materials need to be developed and identified. According to the relevant requirements for representative applications of WC bearings, two materials development loops were performed. Samples were supplied for tribological materials tests and another characterisation method. The results of the tribological tests have so far been very promising: Friction values were very low even in unlubricated tests, and the wear rates are moderate to low.

<u>Finished activities:</u>

T5.1: Material and design specification described in D5.1 report (LBRT)

T5.2.1: New compounds developed by pre-selection of available bio-polymers and fillers, material loop 1&2 (UBRIS/FHF)

T5.2.2: Design microwave source for MW-extruder fixed (IDE/FHF)

T5.2.3: Retrofit MW-extruder system at FHF nearly finished (FHF)

T5.3: Manufacturing WC samples with lab-extruder and by warm pressing (FHF)

T5.4: Testing matrix (based on int. standards) for base materials and WC available (ISQ)

T5.5: Set-up tribo-tests with selected standards and selection of polymer benchmark materials (FHF)

T5.5: Tribological testing of WC samples derived from two material loops and benchmark samples (FHF)

<u>Ongoing Activities:</u>

T5.2.2: Pre-evaluation microwave system and its integration to MW-extruder at the FHF facility (IDE/FHF)

T5.2.1: Further material development (material loop 3) and base material characterisation based on results in T5.5 (FHF/UBRIS)

T5.3: Eco-Design sliding bearing to Labrenta´s machine (LBRT/NCC/FHF)

T5.4: Investigation on WC samples according to the defined test matrix (ISQ)

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Abbreviations

AI – Artificial Intelligence

DMP – Data Management Plan

DR – Air flow (%)

DSC – Differential Scanning Calorimetry

FTIR – Fourier Transform Infrared Spectroscopy

GA – Grant Agreement

I_{cl} – Clothes' Thermal Resistance ($m^2 \cdot °C/W$)

ICT – Information and Communications Technology

ISO – International Organization for Standardization

ISO VG - International Standards Organisation Viscosity Grade P_a – Partial pressure of water vapour in air (kPa)

PMV – Mean Expected Vote

PPD – Expected percentage of dissatisfied

RH – Relative Humidity

SEM – Scanning Electron Microscopy

T – Task

T_a – Forced ventilation room temperature (°C)

T_g – Globe temperature thermometer (°C)

T_o – Operating temperature (°C)

T_r – Average radiant temperature (°C)

T_w – Forced-air wet bulb temperature (°C)

TG – Thermo-Gravimetry

TU – Turbulence intensity

v_a – Air speed (m/s)

WC – Wood Composites

WP – Work Package

1. Introduction

1. Purpose of this document

The purpose of this document is to describe the progress in developing and evaluating WC materials for use in tribological applications, especially for slide bearings. It is summarised, which WC composite materials have been synthesised. The reported results focus on the tribological properties that have been obtained in friction and wear standard tests.

Based on these tribological investigations, a pre-evaluation of different material types was made. The goal was to identify and select promising material types. Moreover, recommendations should be given for further improvement of the tribological properties, but also identify possible risks and drawbacks of the materials. This pre-selection of material types helps focus further research work to enhance efficiency in the production by microwave technologies and reduce the efforts for further investigations, including materials testing and analyses, prototype testing of bearing components and, eventually, assess environmental aspects like recyclability and CO_2 footprint.

1. Need for new materials to mitigate environmental footprints

As already reviewed in D5.1, steel, polymers and other materials are currently being used by the bearing industry for the manufacture of different bearing components. These bearing materials undergo different heat treatments and processes to attain the desired properties to maximize bearing life and performance. However, this leads to the emission of tonnes of CO_2 for every tonne of steel produced, plus the usage of heavy metals (mainly Pb, Cd, Sb, Cu and Sn), which are used in metallic bearings and are extremely dangerous for the environment. At the moment, there is no possibility to reduce the carbon footprint of conventional bearing materials.

From a greener perspective, the use of biobased materials aims to reduce the environmental footprint of the manufacturing process of these materials, reuse wood waste from other industrial or natural sources, and reduce maintenance costs. This goal can be reached by using materials that are derived from renewable sources like wood, with the added benefit of reducing the environmental impact related to its manufacture and improving their circularity.

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2. General Workflow

The general workflow in this project is visualised in fig. 1 (reproduced from the project proposal). To develop a wood composite value chain, the work starts with the selection of base stocks for bio-based composite materials. The development of promising materials is performed in parallel to the definition and preparation of a microwave-enhanced extrusion process to realise high production efficiency and high material quality. Despite a focus on tribological applications, mechanical testing and several analyses methods are necessary to assess the material quality. Tribological investigations will be performed on three levels: Lab-scale friction-and-wear testing of materials; lab-scale testing of slide bearings of standardised shape; demonstration of slide bearing functionality and performance in a technical application. Finally, a TRL6 will be reached by demonstration of the performance of bearing prototypes.

Moreover, concepts for circularity e.g., by re-use of bearing components milling and re-shaping of WCB will be discussed in the project.

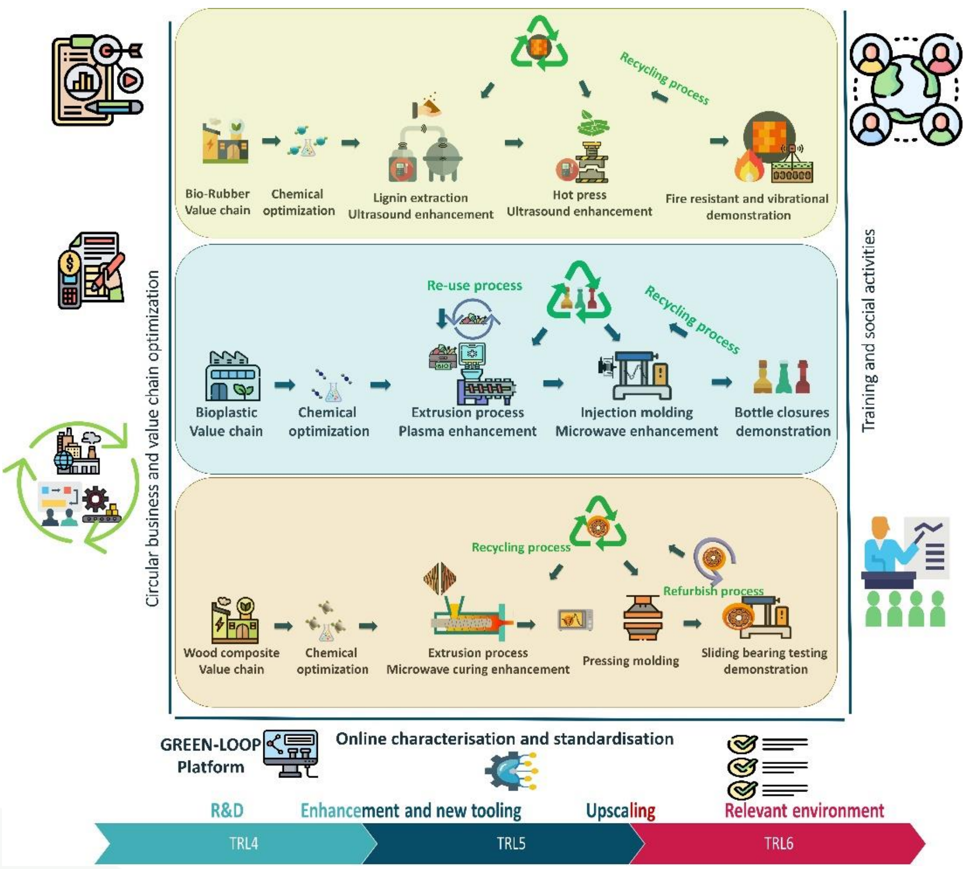

Figure 1: Graphical abstract of the Green-Loop project proposal (reproduced from full proposal)

2.2 Standardization

The bio-material used for the sliding bearings is be produced in accordance with the following standards (inn accordance with Annex A of the deliverable 5.1):

- ASTM D6866
- EN ISO 14125:1998
- EN ISO 1183:2019
- EN 15534-1:2014-04
- ISO 4378
- ISO 6691:2021
- ISO 4178-2

Further explanations for these standards are included in the deliverables 2.4 and 2.5: “Standardisation landscape for biomaterials”.

2.3. Data management

The management of this WP’s data will involve several tasks from this and other WPs: task T1.4. “*Inline monitoring and quality controls*”; task T3.3. “*Upgrades and modifications of equipment in manufacturing lines*” and task T7.6. “*Open science and Data management plan*”.

Throughout the duration of the project, IRIS will coordinate the collection of data from the three manufacturing lines onto the ICT (Information and Communication Technology) infrastructure that will be connected to the GREEN-LOOP platform for the purpose of optimizing the entire value chain, as well as the market analyses and identification of replication cases performed in WP7.

Additionally, to comply with the GDPR, RWTH AACHEN will also publish a Data Management Plan (DMP) that establishes the guidelines for data management (including the data collected, the data processed in the GREEN-LOOP platform, and the results obtained) throughout their entire lifecycle. This information will be published during M06 in deliverable D7.11 "*DMP and open sourcing approach*".

2.4. Circularity

In total, the activities performed in GREEN-LOOP aim to achieve a reduction in CO_2 emissions by 28% and waste material by 40%. To assure circularity and low environmental impact of the products it is necessary to develop solutions either to refurbish bearing components for reuse or to recycle the materials and produce new bearings from recycled base stocks.

A detailed list and a more deepened discussion will be presented in D2.1 *“GREEN-LOOP circular economy evaluation*”.

2.5. Modelling

Modelling will be carried out by NCC as per task T5.3 “*Modelling, Eco design and manufacture of wood-based composite materials*”, supported by AI models from task T2.5. All materials will be characterized by several methods such as TG/DSC, FTIR, SEM and grain size distribution. Samples and components with simple geometries will be manufactured by extrusion and press moulding. Quality controls on the WC samples will be performed by FHF and NCC by using non-destructive methods such as x-rays or ultrasonic.

2.6. Manufacture

Production of wood-bearing samples was done by FHF in collaboration with NCC and UBRIS (T5.4).

The extrusion process was performed and optimized by FHF using bio-based raw materials, in which samples for tribological testing and mechanical characterization will be preferentially performed in net-shape design.

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The surface of the specimens will be machined to ensure certain lubricant retention. Compression tests according to ISO 604 will be carried out to guarantee a minimum strength of the samples prior to the tribo-tests.

The compression moulding will be carried out at NCC using a hydraulic press and metallic tooling to produce panels. The panels can then be machined into the correct geometry for the slide bearing as defined above.

The panels will be pressed at the NCC using a HARE press. Some specifications of the HARE press:

- Platen Size = 0.6m x 0.6m (Maximum Tool area = 0.5m x 0.5m)
- Maximum Ram Stroke / day light = 0.5 m
- Max Pressing Pressure = 1,000 kN
- Max Closing speed = 300 mm/s
- Max Tool weight = 250 kg
- Maximum Platen Temperature = 400°C / 2°C per min (No Closed loop control)

2.7. Tribological testing and evaluation

Lab scale tribological testing of WC-bearing materials and components will be performed by FHF (T5.5); this will include basic materials tests like Pin-On-Disc-Tests to determine friction coefficients and wear characteristics. These tests will enable the screening of materials to identify the most promising candidates for bearing materials, investigate tribological mechanisms and give advice for further materials optimisation possibilities.

For component tests, a basic bearing geometry will be used (see Section 3.1). These tests will be used to obtain information about general tribological behaviour and application-like conditions and thus evaluate the possibilities and limitations of WC for slide bearings, in general.

2.8. Demonstration

The products will be tested in an industrially relevant setting at LBRT’s facilities. The sliding bearing will be substituted in one of the available injection moulding machines to test their performance during the production of bottle closure. This demonstration overlaps with WP4 as one or more production cycles will produce samples with the bioplastic developed in said WP.

Iterations with T5.4 and T5.3 will be done to ensure the proper results at TRL5.

3. Results and Discussion

3.1. Requirements

Specifications and applications of the bio-based wood composite were defined in D5.1 according to the current state, and characteristics of the materials in use are given in the following table.

Table 1 Technical requirements for the wood composite final product

Product	**Wood Composites**	
Physical Properties	**Value**	**Units**
Density	Not relevant	-
Micro-porosity	Favorable to retain lubricant in the sliding contact	-
Water absorption	Acceptably low	-
Mechanical Properties	**Value**	**Units**
Tensile strength	> 50	MPa
Compressive strength	> 70	MPa
E-Modulus	> 1000	MPa
Thermal stability	Up to 150	°C
Tribological Properties	**Value**	**Units**
Wear Coefficient	$< 10^{-5}$	$mm^3/(Nm)$
Friction coefficient	< 0.1 under lubrication < 0.3 under dry sliding	-
pv-value	> 0.3	MPa · m/s
Working conditions	**Value**	**Units**
Temperature	0 - 100	°C
Lubrication	Oil, grease	-
Standards to address		
ASTM D6866, EN ISO 14125:1998, EN ISO 1183:2019, EN 15534-1:2014-04, ISO 4378, ISO 6691:2021, ISO 4178-2		

3.2. General Shape and sample preparation for mechanical and tribological tests

Up to month 12, two material loops have been performed to produce an appropriate wood composite by using different formulations.

The manufacturing process for the wood composites involves, in the first step, mixing the bio-based polymer with suitable wood fibres and carefully choused fillers to improve the tribological properties of the composites as well as to make the mixed compound susceptible to microwave radiation. For the mixing process, an Eirich mixer is used as the first stage. During the second stage mixing, the compound is process using a laboratory size single-screw extruder. The final step involves test samples preparation using a moulding dye and a warm press machine.

In the first wood composite material loop (V205-V219) a commercially available bio-resin wood fibre compound and graphite powders as fillers were used. Different graphite types in different concentrations were added to the base formulation to obtain a good sliding performance of the wood composites.

Since the friction testing results of these WC from the first loop (s. Section 3.4) showed that the wear rates were too high, other additives were integrated into the compound in the second WC material loop (V 231-V244). Moreover, other base materials were chosen to increase their thermal stability.

Four different reference materials based on polymer PA46 (TW341, TW371, TW200F6 and TW271F6) were chosen as benchmarks.

The third materials loop in the next period will concentrate on the fine tuning of the most promising recipes of and, moreover, on the improvement of the manufacturing parameters during their processing. Since these recipes were performed with the small lab-extruder the next step will be to process these compounds with the MW-extruder in a larger scale.

3.3. General Shape and sample preparation for mechanical and tribological tests

Samples for tribological tests were prepared from extruded plates of various material types. Benchmark materials were supplied by the company DSM in the form of plates to prepare samples with the same shape as the wood composite materials. The sample geometry is shown in Figure 2.

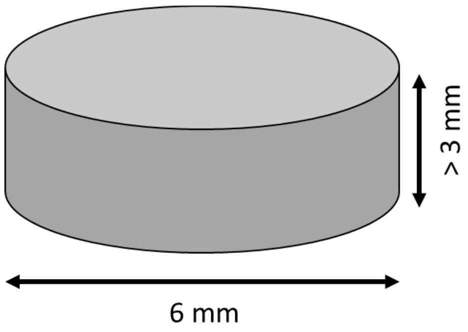

Figure 2: Sample geometry for tribological lab test

3.4. Tribological tests and test conditions

Tribological tests were conducted using a pin-on-disk tribometer (TRM100, Wazau, Germany). New sample holders were constructed to fix the sample shapes (s. Figure 2) against standard bearing rings made of 100Cr6 steel (Hardness HRC > 60). Pictures of the tribometer and the test setup are shown in Figure 3. In this tribometer, the rotating shaft with the steel rings as counter materials is on the upper side. The composite samples are fixed on the lower side.

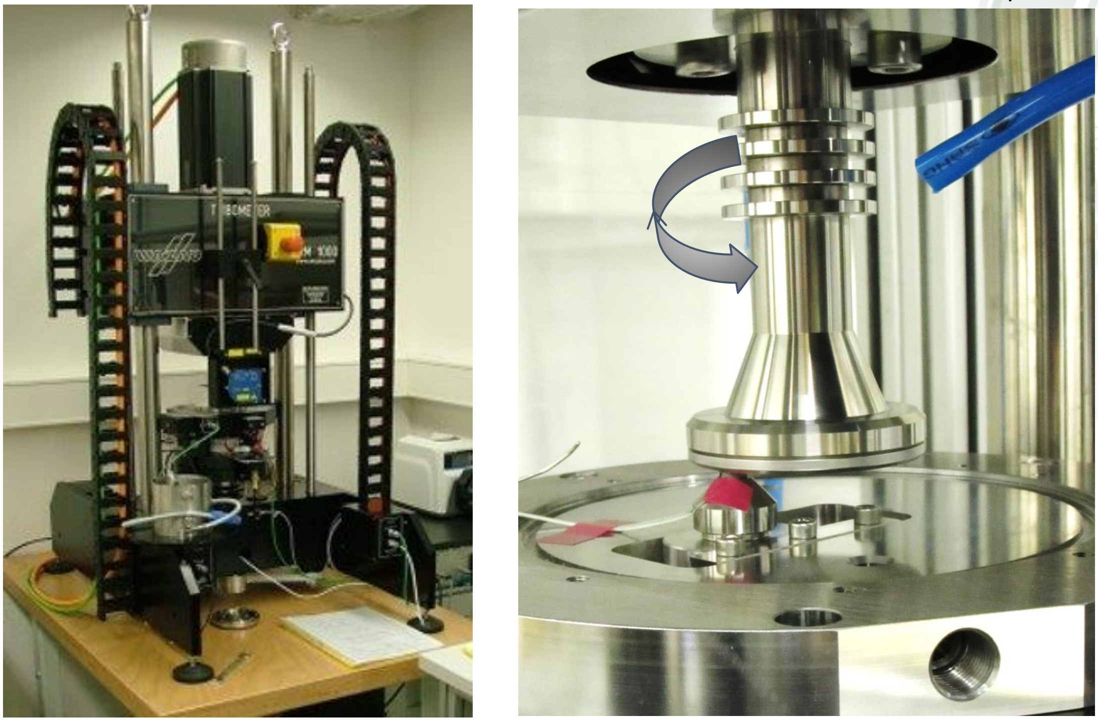

Figure 3: Tribological test rig (TRM 1000, Wazau, Germany) and test setup.

The test conditions of this test series are given in Table 2.

Table 2 Test conditions

Normal force	85 N
Contact pressure	3 N/mm²
Sliding velocity	0.1 m/s
Temperature	room temperature
Test duration	6 hours
Lubrication	dry (air at medium rel. humidity)

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4. Results and discussion

4.1. Material properties

Materials for sliding bearings must have high strength, high thermal stability and density.

At FHF, compression strength tests were performed by using standard ISO604. Test samples should fulfil the required compression strength level of > 70 MPa and Young's Modulus > 1000 MPa.

Samples of the first loop (V205-V219) revealed strength values up to 95 MPa and Youngs Moduli < 1000 MPa and couldn´t fulfil the requirements. Specimens from the second WC material loop (V 231-V244) also showed sufficient compressive strength.

Further results on material properties are within the scope of Task 5.4 of the project and will be reported in a separate deliverable.

4.2. Evaluation of friction and wear results

Depending on the material type, the friction values varied significantly. Many WC material types showed quite stable COF values in the range of 0.3. This friction level is typical for state-of-the-art polymer composites for tribological applications and was also reached by benchmark composites containing PTFE fillers to reduce friction. Corresponding wear evolution curves also indicate a broad range of wear resistance.

Very interesting results were obtained for the second loop of material types (V231 to V244): Five out of seven material types reached friction values lower than 0.25. For dry friction of composite materials, these values are very low.

Wear results are expressed in the form of wear coefficients, which are defined as wear volume loss, divided by normal force and sliding distance. For both COF and wear coefficients, low values are aspired.

The wear coefficients were in the range of 10^{-3} $mm^3/(Nm)$, which is already acceptable for unlubricated cases and comparable to polymer benchmark composites based on PA4.6. Regarding the requirements for the WC materials (s. Deliverable 5.1), several material types are expected to have sufficient tribological properties to be used for WC slide bearings.

Details of the results must be kept confidential and, therefore, cannot be disclosed in this public report.

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5. Future workflow and Upscaling

The possibilities for the implementation and use of WC slide bearings are being discussed. Several possibilities have been identified, but more discussions are needed to evaluate the possible chances and risks for these possibilities and choose a promising case for the demonstration of the project results.

The further development of the WC bearings will follow the work description of the WP5 of the Grant Agreement (GA) as well as the general workflow described in section 2 of this report. This will include materials and manufacturing development, lab-scale analysis, and testing activities.

It must be checked, if there is a chance to apply for a patent to protect the novel developed material and manufacturing know-how.

Manufacture of the bearings will be done either by extrusion only or by extrusion followed by compression moulding with the enhancements detailed in task T5.2 “*Upgrades and modifications of equipment in manufacture lines*”.

During M06-M025 will be performed in task T5.3 “*Modelling, Eco-design and manufacture of wood based composite materials*” and T5.4 “*Generation of samples, characterization and quality control*” a continuous work of data control and upgrades to deliver a solid prototype.

The extrusion of these prototypes with the final geometry will be tested at TRL6 in industrial setting by LBRT. All quality characteristics defined previously will be constantly reviewed during M25-M36 in the activities of WP6.

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6. Conclusions

After defining the specifications for wood-based composites materials further work was performed according to the work plan of Green- Loop. The specifications are a guideline for subsequent tasks within WP5, i.e., to find, manufacture and evaluate suitable compositions and eventually demonstrate their use as technical bearings.

It is necessary to define which machine model will be used to test the bearings as the information for the part to be substituted will vary accordingly. As previously stated, due to the quantity of samples necessary, it is likely that the smallest machine will be utilized. Typically, larger machines are employed for extended-duration manufacturing, whilst smaller machines are more suited for short-duration productions and product testing. Consequentially, this choice will affect measurements and characteristics of the bearing features themselves.

Lab scale demonstration and evaluation will help define and find ulterior attributes of the WC bearings, which will also affect the products obtained in the bio-plastic value chain during WP4, as LBRT is the manufacturer. Finally, the last tasks of the WP5 will be to evaluate the tribological performance of the WC materials and bearings to demonstrate their feasibility for technical use.

Recent results on tribological behaviour have been very good and may be regarded as a success. Patent relevance is currently being checked. Disclosure of the relevant results is currently subject to the creation of a patent. Therefore, a large part of this information had to be omitted in this public deliverable.

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