Comprehensive overview of the project

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1. Introduction

The pilot and demonstration project RollOilFree II aims at testing Oil Free Lubricants (OFLs) under industrial conditions for the cold rolling of packaging steels and steels for the automotive industry, as well as to demonstrate the subsequent processability of the rolled steels down to the coated end product.

The present document provides an overview of the project approach, presents the addressed problems and challenges as well as the methodological approach that is carried out by the Consortium to address such challenges.

1.1 Contents of the document

The remaining part of this document is divided into 6 main sections:

- Section 2 describes the challenges addressed by the project and the targeted objectives.
- Section 3 analyses the state of the art concerning the use of the OFLs in cold rolling of steels and the progresses foreseen as a result of the project.
- Section 4 describes in detail the methodological approach pursued in the project.
- Section 5 summarised the impacts foreseen for the project.

2. Problem description

The lubricant in the cold rolling process must fulfil high requirements regarding its functional properties, e.g. cooling, lubrication, and cleaning. These functionalities highly influence the productivity, the process stability, and the product quality. Beside this also the compatibility with subsequent processes and requirements arising from the final use cases is of high importance.

Commonly, conventional oil-based lubricants (emulsions) are used in the rolling processes. During the rolling process, this emulsion gets contaminated with wear particles and tramp oils. In addition, sludge (wear particles with deteriorated / cracked oils) accumulates in the tank system and the filtration / skimming processes are not perfectly efficient. Also, production losses due to the fluctuations of the emulsion conditions are reported. Summarising, the high effort in maintenance and care and insufficient product quality requires for alternatives.

In a previous project named RollOilFree[1], oil-free lubricants (OFLs) were developed as substitute to the conventional oil-based lubricants in steel cold rolling. Pilot tests revealed comparable or even better application properties. The attempt of an industrial verification of those results was not successful as it became apparent that for use of OFL in industrial mills process engineering adjustments are necessary. For a successful transfer of OFLs into the industrial standard it is therefore essential, beside a further adaptation of the OFL itself, to also perform extensive trials under industry-related conditions accompanied by necessary process engineering modifications. Thus, it is possible to make the next step into a fully industrial application and to benefit from the great advantages the OFLs offer in terms of maintenance, care and disposal beside their already good rolling related property profile. In addition to the results gained in RollOilFree also the very positive experiences of the industrial application in the aluminium industry can be mentioned, where beside technical advantages also economic as well as ecological benefits were highlighted.

The ecological assessment of the impact on global warming potential over the entire life cycle in RollOilFree1 shows that OFL and conventional oil-based lubricants perform almost equally well. However, palm oil-based lubricants, which are currently used for cold rolling of packaging steels, were not considered. Substitution of these lubricants by the new OFLs should yield significant environmental benefits because palm oil is more harmful to the climate than fossil raw materials. Further, the increasing number of palm oil plantations is destroying rainforests and causing significant environmental and social problems in the producing countries.

2.1 Objectives of the project

This project aims on the successful transfer of OFLs into the industrial standard of steel industry and by this, help to evolve steel industry towards a greener production. This will be done on the example of cold rolling of steel grades for the packaging and automotive industries.

[1] RFCS-2015-709504: Steel cold rolling with aqueous oil-free lubricants (RollOilFree) (30/06/2020)

Taking the results from the RollOilFree project into account, this will be achieved by further optimisation and adaptation of OFLs to the specific needs resulting from the industrial rolling and subsequent processes accompanied by extensive industry related rolling tests allowing the evaluation of long-term and process relevant characteristics.

To realise this, the main objectives are:

- Adaptation and optimisation of OFLs to the specific cold rolling requirements for the automobile and packaging industries.
- Providing long-term stability of the adapted OFLs.
- Examination of the need for adaptation of the rolling process engineering to the OFLs specific characteristics.
- Development of online monitoring for OFLs.
- Ensure cold rolling of steels with OFLs.
- Guaranty of trouble-free further processing in the subsequent production steps.
- Providing of adapted technologies regarding OFL care, recycling and disposal.
- Providing guidelines for the successful transfer of OFL to the industrial standard and cost estimation.

3. Advances promoted by the project

3.1 State of the art

According to the current state of the art, neat oils and oil/water emulsion are standard lubricants in hot and cold rolling processes[2]. Efforts mainly focused on the lubricant modification as well as on the application during the rolling process[3]. Laborious control measures were taken to maintain the lubricant system on a proper working level[4]. Cleaning and reconditioning concepts for lubricants are presented in literature[5] as well. Their drawbacks and especially their limited potential to meet environmental regulations resulting into high and cost intensive efforts require for alternatives.

The substitution of oil/water (o/w) lubrications by OFLs has become increasingly important for the next generation technologies in the hot and cold forming areas. Beside purely technical functions these lubricants will need to fulfill more societal demands such as environmentally friendliness / biodegradability and sustainability criteria[6]. Promising scientific approaches are the application of polyalkylene glycols (PAG) and polymer lubricants.
Up to now oil containing emulsions are the industrial standard for lubrication in cold rolling of steel. In conventional tandem cold rolling it is estimated that around 40-50% of the total rolling oil consumption is due to care and maintenance processes and especially due to the magnetic separators.

Concerning the use of OFL for automotive steel grades cold rolling, oil concentrates for emulsions are mainly based on natural and synthetic esters produced from vegetable oils and most frequently from palm oil. The part of emulsion oil concentrates that is based on vegetable oils such as palm oil can amount up to 75 or 80%. The rest of the products consists of a number of different additives, such as emulsifiers or EP-additives and small amounts of fossil oil.

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[2] Dubey, S.P., Sharma, G.K., Shishodia, K.S. and Sekhon, G.S. (2005), "A study of lubrication mechanism of oil-in-water (O/W) emulsions in steel cold rolling", Industrial Lubrication and Tribology, Vol. 57 No. 5, pp. 208-212.
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Kimura, Y. Fujita, N. a.o.: High-speed rolling by hybrid-lubrication system in tandem cold rolling mills, Journal of Materials, 2015
[4] Blees, R.; Karzewski, M.; Kompernaß, H.: Inline measurement of rolling emulsion concentrations at Wickeder Westfalenstahl, MOT International 4/2006, p. 66 – 68
R. Monden, Method for inspecting lubricating oil composition and method for producing lubricating oil composition US20210222083A1, 2018
[5] Johnsson, A. Developing environmentally friendly rolling lubricants, Journal of Engineering Tribology Part J, 225 (2011), 932-939
[6] Nowak, P et al.. "Ecological and health effects of lubricant oils emitted into the environment." International journal of environmental research and public health 16.16 (2019): 3002
Sagraloff, N. et al. "Development of an oil free water-based lubricant for gear applications." Lubricants 7.4 (2019): 33. Shah, Raj, Mathias Woydt, and Stanley Zhang. "The economic and environmental significance of sustainable lubricants." Lubricants 9.2 (2021): 21.

Therefore, replacing conventional emulsion oils with OFL lubricants will likewise allow to substitute palm oil usage thus preventing deforestation and other negative effects linked to palm oil production.

3.1 Foreseen progress beyond the state of the art

Although OFLs were investigated in rolling processes mainly the rolling of aluminum was focused on and just two projects were dealing with the cold rolling of steel. The results were promising but the **remaining** great **demand** for **industrial-close rolling trials** for the successful **transfer** of gained knowledge into **real** (industrial) cold rolling **processes** is multiply mentioned, not only because of OFLs **good application properties** but also due to their inevitable **high potential** meeting the ambitious **environmental demands**, **cost-efficiency,** and **reduction** of high **disposal** efforts.

Consequently, in RollOilFree, as a Research and Development project, the extraordinary properties of the OFLs were shown in laboratory tests and pilot trials, but a first attempt of industrial trials failed, so the industrial feasibility could not be finally proved. **RollOilFree II**, as a Pilot and Demonstration project, aims on closing that gap and providing feasible concepts for the transfer of OFLs into steel cold rolling as a new industrial standard. This will be investigated for two use-cases: **automotive and packaging steels** which present high requirements. For instance, packaging steels have to have a high stability at thin gauges combined with a good formability for can making. The most important requirement for **automotive steels** on the other hand is superior surface quality and high mechanical strength with nevertheless good workability and excellent coating quality.

RollOilFree II will not stop at testing the lubrication performance in the rolling process but will go much further by providing easy manageable solutions for the complete peripheral processes for the use of OFLs (care, maintenance, monitoring, etc.). Furthermore, to grant an easy transfer into industrial practise and thereby become the new standard for greener steel production, a feasibility study will be done to permit an easy, trouble-free, and widespread adaption in the European cold rolling industry.

In **summary**, it can be stated that there is a **deficit** in the further optimisation and adaptation of the OFLs under **industrial** conditions to be able to capture the specific conditions of the industrial practice of cold rolling steel. This requires for a **testing of the OFLs** under industrial conditions possible on pilot scale and then on industrial level. For this reason, the submitted proposal **RollOilFree II** aims at a deep and extensive investigation of OFLs under pilot trials as well as industrial conditions together with **the provision of guidelines** giving a concept **for easy transfer into the industry** especially for the here specifically investigated use cases automotive and packaging steels. This will be aided by online measuring techniques to control the OFLs and by a mathematical model of the cold rolling with OFLs.

3.2 Research and innovation maturity

In *RollOilFree***Errore. Il segnalibro non è definito.** the applicability of OFLs for cold rolling of steel was successfully demonstrated in principle yet in laboratory scale and pilot trials. Further investigations, e.g. on the compatibility with following process steps as well as the manageability under industrial conditions are mandatory in order to provide a full transfer of OFL into the industrial standard. Adaption and developments will be therefore necessary.

With the industrial cold rolling trials with OFL as well as the influence of this kind of lubricant on the coils in the following processes, it is aimed to **increase the TRL level from TRL 4/5 to reach TRL 7**. Details are provided in **Table 1**.

Table 1. Technology readiness level to be reached in RollOilFree II.

Dissemination activity	From TRL	To TRL	Key Dissemination Message
OFL used for cold rolling of steel	5	7	OFL have been used successfully in *RollOilFree***Errore. Il segnalibro non è definito.** in a pilot plant. In RollOilFree II, it is intended to carry out industrial tests.
Successful workability of the cold rolled steels during the further processes	4	7	The further processes (degreasing, annealing, skin-pass rolling and coating) will be investigated at pilot-scale for the automotive steels and at industrial scale for the packaging steels. In the previous project it was done at a laboratory scale.
Adapted technologies regarding OFL care, recycling and disposal	4	7	Development of a new monitoring system for OFL including adapted technologies for the care and maintenance to be implemented at an industrial scale. In the previous project, it was only investigated at a laboratory scale.

4. Methodology

4.1 Concepts and methodological approach

In the previous RollOilFree project, the long-term stability tests of the OFLs revealed excellent characteristics such as reduction of lubricant replacement. The OFLs did not show any corrosive potential on installations and the lubrication profile remained consistent. This resulted in a reduction of the use of inhibitors. In addition, OFL showed excellent ageing properties in an extended high-shear pump-spray-test. No signs of deterioration of lubricant properties or degradation processes could be observed in more than six weeks of accelerated ageing.

The expenditure for maintenance and care can be considered as reduced and therefore the OFLs can be regarded as advantageous in comparison to common oil-based emulsions. In addition, beside the assessment of eventually necessary process engineering efforts, the lubricant monitoring also needs to be adapted. Here, not only OFL will be established as substitution for o/w lubricants, but also sensor technology will be directly implemented.

Consequently, in RollOilFree, as a Research and Development project, the extraordinary properties of the OFLs were shown in laboratory tests and pilot trials, but no industrially feasible solution has been provided. Now that gap shall be closed and feasible concepts for the transfer of OFLs into steel cold rolling will be provided.
Multiple steel grades will be chosen for their specific use in the **automotive and packaging industry** for the extensive industry related rolling trials. The different requirements for the OFL arising from these specific process routes will be taken into account during the adaptation of the OFLs.
In **RollOilFree II**, a systematic **adaptation of OFLs** to **characteristics guaranteeing** a **packaging and automotive use compatibility** will be done. The interdependencies between the different tasks are described in **Figure 1**.

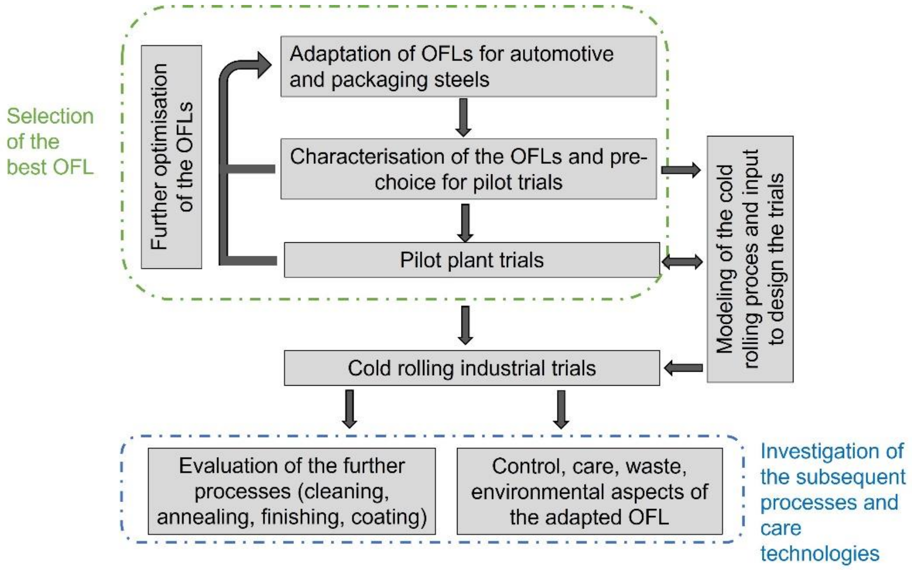

Figure 1. Steps to be performed in RollOilFree II to ensure a successful transfer into the industry.

The evaluation of OFLs for cold rolling of steel not as a laboratory scale study but as the future industrial standard for steel cold rolling contains more than only the assessment of the lubrication performance. Recycling, waste treatment, possible effects on the following process steps (cleaning, annealing, skin-pass rolling and coating), as well as on the product quality must be taken into account. Therefore, a thorough overall evaluation concept for assessing the impact of the OFLs on the production process of automotive and packaging steel will be performed. The ecological evaluation regarding the impact on the global warming potential over the whole life cycle shows almost equal performances between OFLs and oil/water lubricants in RollOilFree. A product life cycle assessment will be also carried out in this Pilot & Demonstration project.

Additionally, the feasibility of the product switch will be proven and transferable guidelines for a successful implementation will be provided.

The applied methodology is described in the following.

4.1.1 Requirement matrix

The process parameters in both cold rolling mills will be collected and the emulsions currently used for the automotive (**Thyssenkrupp Steel Europe AG** - TKSE) and the packaging (**Thyssenkrupp Rasselstein GmbH** - TKPS) steel cold rolling will be characterised and will serve as reference for the whole project. The final requirement matrix for the OFL will result from the information gathered from both cold rolling mills.

4.1.2 Adaption and characterisation of oil-free lubricants

OFLs are lubricants that do not contain mineral oil, natural triglycerides or synthetic esters, which are non-polar molecules that can only be taken up in an industrial coolant by emulsification or dispersion. These molecules are responsible for some of the mentioned issues with respect to maintenance, care and product quality. OFLs are characterised by good water solubility of the main components compared to the conventional oils. Due to their solution-like properties, they can be easily washed off the product, are immiscible with tramp oils and have a low tendency to adhere to particles. In addition to avoiding particulate and lubricant residues on the product, maintenance of the lubricant should therefore also be facilitated by the simplified removal of tramp oils and particles.

The optimisation of OFLs at **Quaker Houghton B.V.** (QH) for the selected cold rolling processes and steel grades will be part of the project after the generation of a requirement matrix. One optimisation route is reserved for PAG (poly-alkylene glycol)-based lubricants focusing the positive outcome of RollOilFree. The other optimisation routes are open for other promising formulations based on water-soluble polymers as base fluid. In both routes, different types (medium / large molecular weight compounds), with different amounts will be used and further optimised with specific water-soluble additives (EP (extreme pressure) additives, friction modifiers, corrosion inhibitors, anti-wear and -oxidation inhibiting additives, etc) to fulfil the specific needs for the different steel types in the scope. Based on pilot mill trials, the OFLs will be further optimised and eventually both routes will be combined.

Some characterisations such as lubrication performance (simulation of roll bite conditions, see **Figure 2**), film formation capacity, plate out properties, corrosion preventing properties, wetting properties, annealing properties, cleaning properties, long-term and chemical stability (see **Figure 3**) will be carried out, to select the optimal adapted OFLs for both, automotive and packaging steels. In addition, the resulting newly optimised OFLs will be evaluated with respect to their environmental and biological properties. All with the goal to meet or exceed the performance of the reference rolling oils in scope and guarantee a robust performance of the OFLs.

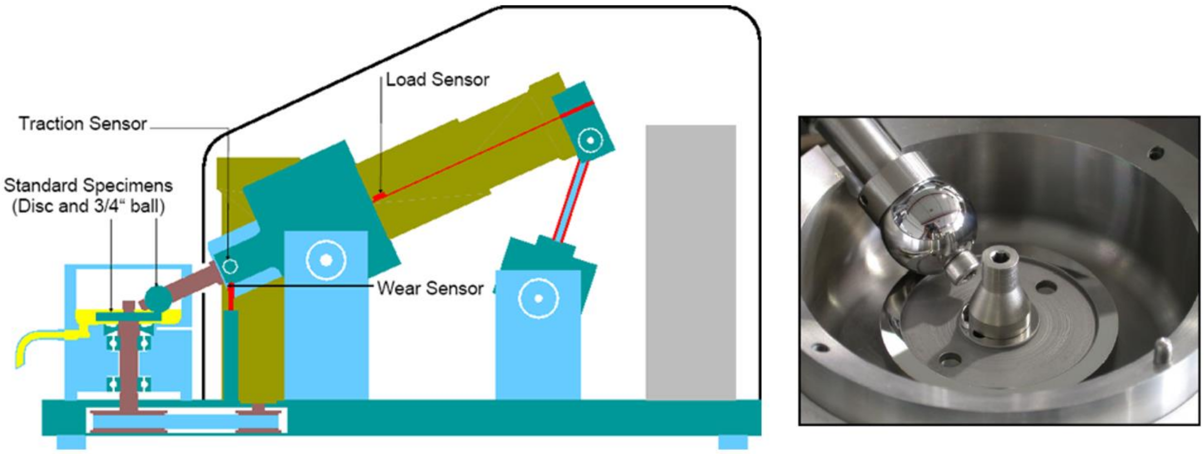

Figure 2. Mini traction machine (performance of the emulsion in the Roll Bite Mimicking Test, RMBT) (QH).

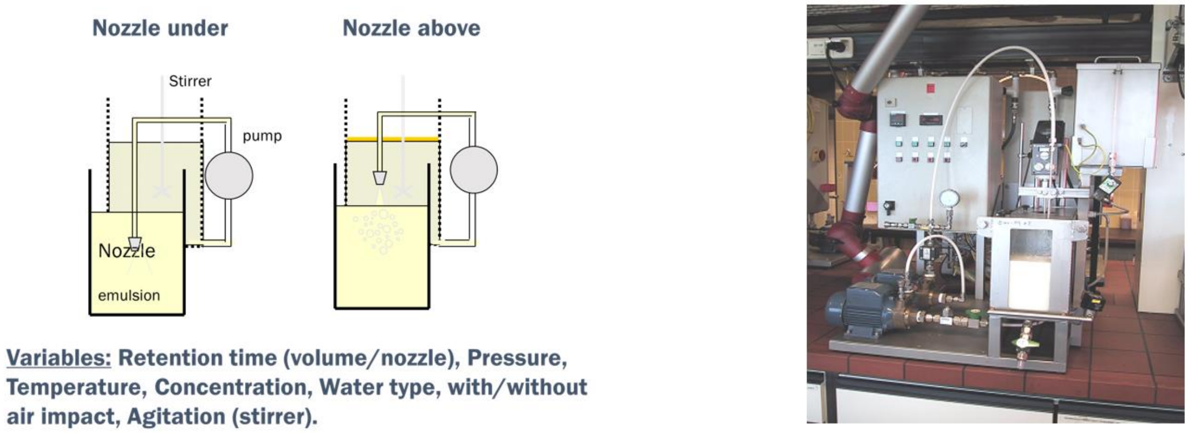

Figure 3. Lubricant recirculation test.

Based on the results from the previous project RollOilFree, further investigations for the successful transfer to industrial applications are essential. In that context, some important questions respectively technical challenges like the influence of the OFLs on:

- the friction in the rolling gap
- the temperature gradients in the work rolls
- the surface pressure while contacting
- the surface contaminations on the rolls as well as on the strip surface as a consequence of possible material abrasions

must be answered.

Therefore, the basic concern is to evaluate the interrelations between the tribo-package of the OFLs and the significant tribological effects on the rolls and the rolled materials. The OFLs adapted by QH will be examined first on the **3-rolls-wear-test bench of VDEh-Betriebsforschungsinstitut GmbH** (BFI) and then on the **pilot plant of Tata Steel Netherlands B.V.** (Tata).

The cold rolling process is a very complex tribological system. The production of precisely defined geometrical tolerances and high surface qualities require the evaluation of the friction and wear behaviour under well-defined mill parameters.

Because of the high technological complexity, investigations at both the 3-rolls-wear-test stand of BFI (depicted in **Figure 4**) and at the pilot plant of Tata are advantageous to select the adapted OFL.

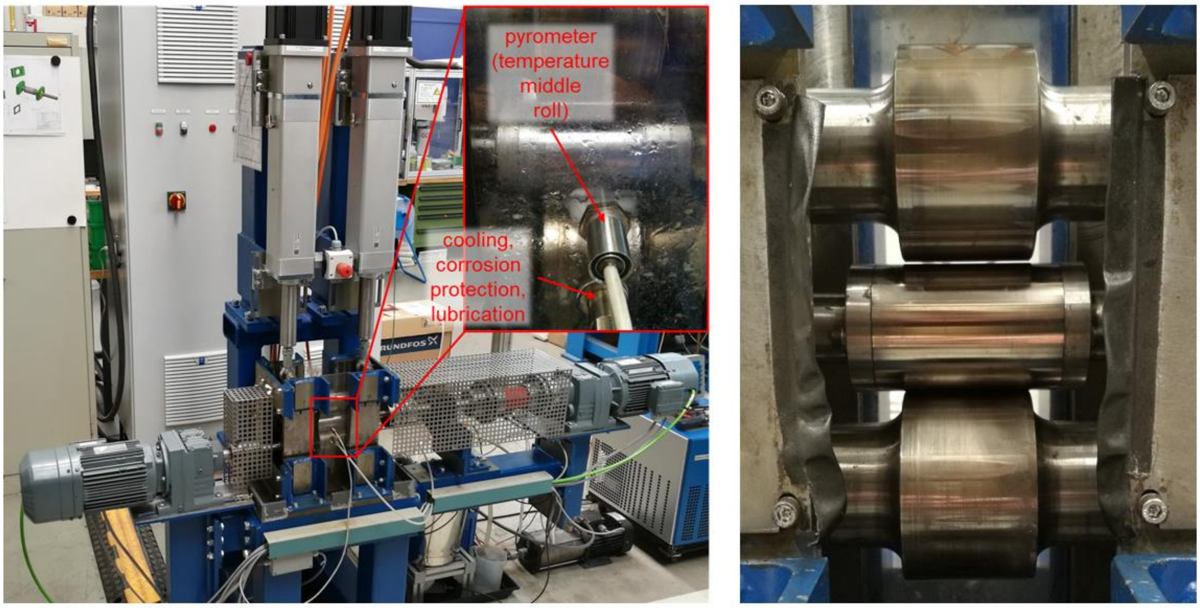

Figure 4. Left: picture of the 3-rolls-wear test bench (BFI), Right: zoom on the 3-rolls.

In the 3-roll-wear-test stand of BFI, the major conditions, like surface pressure, friction, temperature are adjustable and measurable. Nevertheless, after these **long-term tests**, the examination of the contaminations of the OFL is possible. The viscosity and other parameters of the OFLs under these conditions will be evaluated as well. The upper and lower rolls are simulating the work rolls, and the roll in between is simulating the strip to be cold rolled. Regarding the middle roll, simulating the strip, rolls with similar characteristics as the hot strip material will be selected.

4.1.3 Mathematical model of the cold rolling process with OFL

Scuola Superiore Sant'Anna (SSSA) will adapt existing Mathematical Model of Cold Rolling (MMCR) towards OFLs in collaboration with the other partners. The model will serve as a guide, support and investigation tool. Indeed, in this work the use of OFLs for the cold rolling of packaging steels will be studied and this is a novelty. This means that there is no knowledge or data already available for this specific application.

The MMCR will be as close as possible to the real physics of the process and will take into account 3 parts: 1) work roll system, 2) the strip and 3) the lubricant. Parameters such as the velocity, stress, strain, strain-rate, temperature, wear, etc. will be calculated.

From the afore-mentioned basic quantities, it will be possible to calculate several process parameters, such as the resulting force and torque of rolling, the wear volume, lubricant inlet flow, etc. In practice, the post-processing of the results of the simulations carried out with the MMCR will be able to satisfy all the needs of the project.

It is important to specify that the MMCR will not be a "single" model, but rather a modelling context that will generate multiple models, able to satisfy the disparate needs of this part of the project. They may differ in geometric dimension (2D, 3D), in accuracy, in computational cost, in scope, etc. The models for the pilot trials at Tata and the industrial trials at TKPS will be generated from the MMCR.

For that purpose, the MMCR will be parametric and modular. "Parametric" means that the model parameters can be changed, such as the diameter of the work-roll, the gauge or its speed. "Modular" means that the template is a structure of modules that can be modified by adding or subtracting modules or changing their content. For example: you can have 1 or more stands, the strip material module can "contain" different models for different steels, etc.

It is important to underline that, although it is not the main focus of the project, one of the useful products here will be an experimentally verified model of OFL lubrication. This will broaden the knowledge on the subject and give more possibilities to extend the field of application of OFLs in cold rolling, improving the dissemination of the project results.

4.1.4 Pilot trial concept for lubrication performance (TRL 5)

After a **first adaptation and tests on several OFLs, pilot trials** (TRL 5) will be performed at the pilot plant of Tata, which is shown in **Figure 5**.

Figure 5. The pilot plant of Tata.

In comparison to the previous RollOilFree project, it will be possible to roll strips having a width up to 300 mm with an available speed up to 25 m/s. In addition, the maximum rolling force is 2000 kN against 500 kN in the previous project and the torque 5 to 50 kNm (against 2.8 kNm). The work roll diameter is 400 mm (against 150 – 228 mm).

Work rolls are prepared (by grinding) according to normal industrial procedure. In this mill, a direct lubricant application unit (green sprays in the scheme of the pilot plant shown in **Figure 6**) can be used. It consists of one nozzle for top, one nozzle for bottom strip surface. As shown this spray is directed towards the strip.

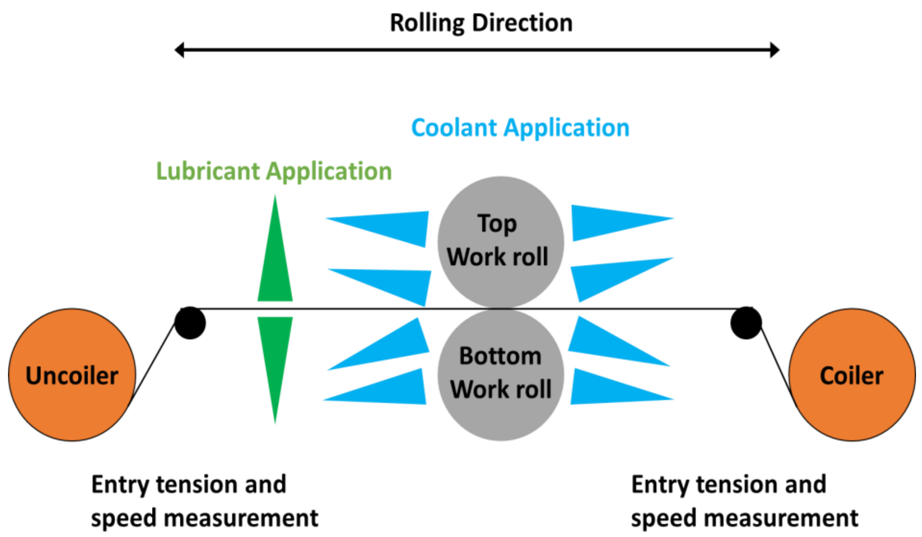

Figure 6. Scheme of the pilot plant of Tata.

Furthermore, the mill is also equipped with a recirculating coolant circuit. Usually, emulsions are applied through 4 cooling headers per side (blue sprays), each header consists of 3 nozzles. This could be used also for the OFL. These sprays are directed towards the work rolls and towards the gap between roll/strip. The major advantage of this pilot plant for this project is the presence of a full emulsion recovery system (clean tank, dirt tank, storage tanks, temperature control, pressure control, filter to clean emulsion coming back from mill), the same as in the industrial mill. This pilot plant is therefore suitable to carry out the work in this project regarding the cold rolling, OFL monitoring, OFL management close to industrial reality.

The pilot plant trials are planned to be carried out in three stages:

- **In the 1st stage**, 3 to 4 OFLs adapted by QH will be tested on the cold rolling Tata pilot plant with automotive and packaging steels supplied by both steel suppliers (TKSE and TKPS).
- **In the 2nd stage**, by evaluation of the results of the 1st step (number of passes, reduction, rolling force, etc.), the OFLs will be further optimised by QH and tested again; first in the laboratory and on the 3-rolls-wear-test stand and then on the pilot plant again. This will

be done by testing more process parameters, such as other work roll roughness, higher strip temperatures and deliberate contamination with other process fluids.

- **In the 3rd stage**, the best OFL will be intensively tested before to test it at an industrial scale.

Figure 7 depicts the methodology to carry out this work. All these parameters will enable to demonstrate the properties of OFLs in a realistic industrial case.

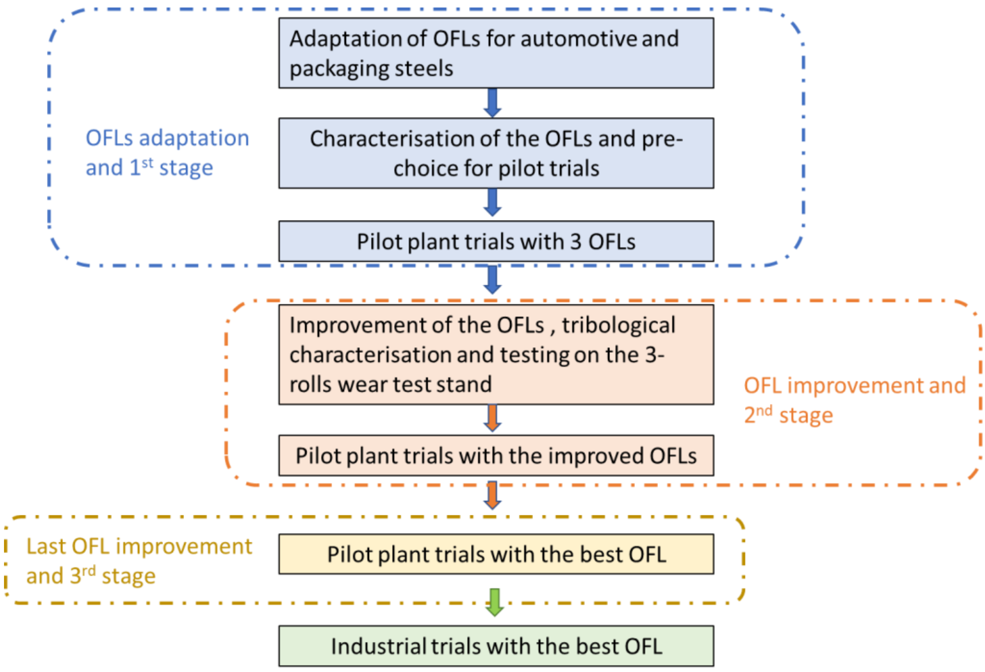

Figure 7. Methodology to improve the OFL and to carry out the cold rolling pilot trials in several steps before the industry trials.

Together with the pilot testing, the long-term behaviour of the OFLs will be evaluated. For that purpose, the evolution of the parameters mentioned previously (pH, temperature, viscosity, etc.) will be determined as well as the bacteria evolution, the lubrication performance, etc. Another part will be dedicated to the care technology such as the recycling properties, the cleaning, the possibility to filter the particles and the lubricant, etc.

4.1.5 Industrial trials

After the cold rolling pilot trials, industrial trials will be carried out at the cold rolling mill of TKPS (see **Figure 8.a**) with the best OFL selected after the pilot trials.

(a) (b)

Figure 8. a) 5 stand tandem mill at TKPS; b) setup of a quarto stand of a tandem rolling mill, consisting of two back-up rolls and two work rolls.

For this process the material has one run through the line and passes five of this quarto-stands (see **Figure 8.b**), that are supported by high strip tension. The two working rolls in each stand are supported by two back-up rolls, that there is no bending. Because of the high rolling forces (several MN) – especially in the last two stands because of hardening of the material – there is a need of a high-performance lubricant, to avoid strip breakages. In every stand there's an increase in speed, because the reduction of thickness means a growth in length, the maximum speed of above 2.000 m/min is reached before coiling. TKPS will test several packaging steels with different thicknesses.

TKPS performs a big maintenance campaign one time per year when cooling water is changed. TKPS will do the industrial trials before this maintenance campaign. TKPS plan to roll 12 coils with OFL. In that case, there is no problem with the cooling water contamination because a new cooling water will be used when the production will start again.

4.1.6 Ensuring compatibility with following process steps

During the industrial trials at the cold rolling mill of TKPS, packaging steels will be cold rolled with the best OFL and the subsequent processes (degreasing, annealing, skin-rolling and coating) will be as well assessed.

In addition, the automotive steels coils rolled at the pilot plant of Tata will be investigated as well at TKSE regarding their behaviour towards the subsequent processing.

Contrary to TKPS, they will evaluate these processes at larger pilot scale or for the annealing process at an industrial scale (see **Figure 9**).

Figure 9. Batch annealing at TKSE Bochum.

The degreasing process will be investigated in a in **continuous pilot degreasing line** at TKSE Dortmund. The **skin-pass rolling** of annealed pilot coils will be assessed in pilot-cold rolling line at TKSE Dortmund.

Regarding the coating, 2 options can be selected:

- **Hot dip** galvanizing of pilot coils in **continuous pilot HDG-line at TKSE** (see **Figure 10**).
- **Electro** galvanizing of pilot coils in **continuous pilot galvanizing line** at TKSE (see **Figure 11**).

The **strip quality** after the cold rolling and after the finishing processes will be investigated in both cases, taking into account the strip surface quality, the roughness, the cleanliness properties, etc. An in-depth analysis of the as-rolled surface, which includes the determination of surface texture, absence of possible surface defects as flaps, scratches, stains, roughness, etc. will be made. Additionally, a chemical analysis of surface residues, possible degradation products of lubricants, amount of organic contamination as well as iron fines will be carried out.

After the surface has been thoroughly characterized, subsequent process steps will be evaluated and analysed and it will be decided if alterations or adaptions of the OFLs are necessary. The laboratory tests that are done are for example the “carbon value” test, that shows the exact amount of residual carbon (organic and inorganic) on the surface and several degreasing tests like the “q panel test” or an electrochemical degreasing test.

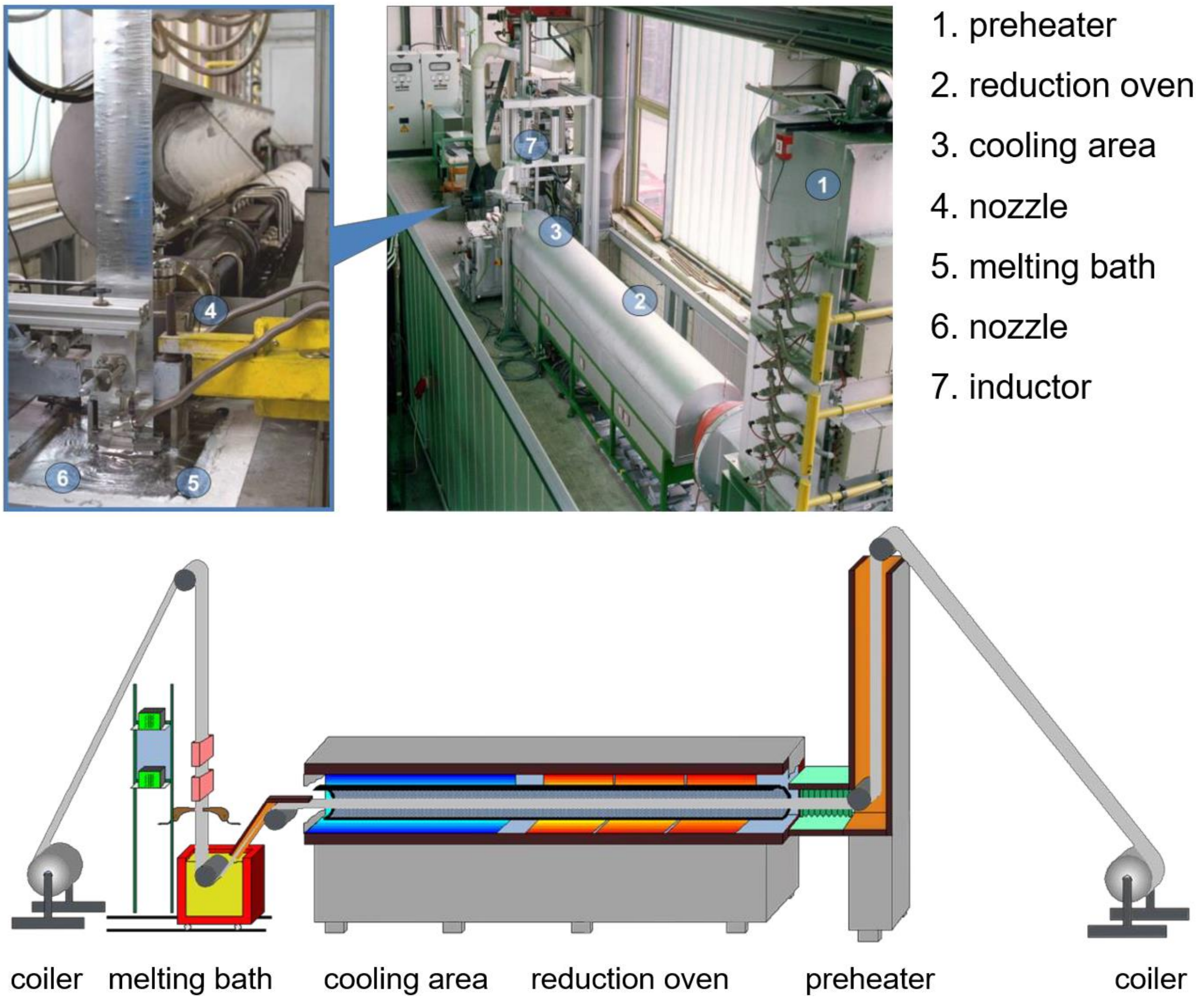

Figure 10. Hot dip coating pilot line (TKSE).

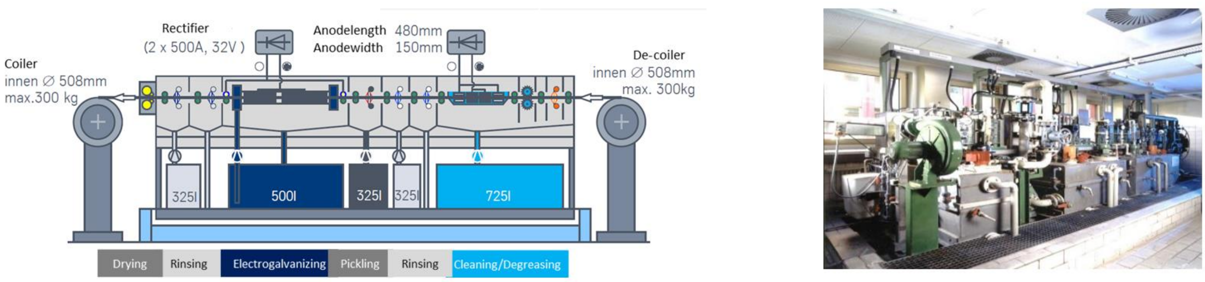

Figure 11. Electro galvanising pilot line (TKSE).

4.1.7 Lubricant care and wastewater system for OFLs

The current techniques such as the oxidation with H2O2/ UV and evaporation will be evaluated regarding the wastewater treatment. Since these techniques are energy-intensive and increasingly expensive, attempts are also made to retain the main organic components, which are present in the form of water-soluble organic polymers (i.e. PAG), by ultrafiltration. For the lubricant care, it is intended to experiment several methodologies such as the skimming, the ultrafiltration and the magnetic filtering.

Together with the pilot testing, the long-term behaviour of the OFLs will be evaluated. For that purpose, the evolution of the parameters mentioned previously (pH, temperature, viscosity, etc.) will be determined as well as the bacteria evolution, the lubrication performance, etc. Another part will be dedicated to the care technology such as the recycling properties, the cleaning, the possibility to filter the particles and the lubricant, etc.

4.1.7 Guidelines for conversion from the usage of oil-based lubricant to OFL

Tata, TKSE and TKPS will determine how steel producers could switch from the usage of oil-based lubricant to OFL. They will evaluate the equipment needed (pump, lubrication system, tank, disposal equipment, etc.) with the support of QH. All costs for this transfer will be estimated. Before to start the industrial trials, TKPS will modify its mill to be able to cold roll steels with OFL. The requirements and adaption needed due to subsequent process steps such as the degreasing, annealing, skin-pass rolling and coating will be also taken into account. In this frame it is also planned to extend the current online lubricant monitoring (currently only the oil concentration is measured) in order to capture the overall OFL key parameters that have to be monitored continuously. An existing measuring device including suitable sensors will be adapted for that purpose and will be tested with both, current emulsions and with the OFLs adapted by QH. This will be installed in the Tata Steel pilot plant to investigate whether it can be used to monitor properties of the OFL that affect lubricant performance.

Finally, the technical and economic feasibility will be evaluated and with the information gathered within the project, it will be possible to provide guidelines to ensure a successful transfer of OFL into automotive and packaging steels industry.

4.2 Models and assumptions

In conventional tandem cold rolling it is estimated that, in a mass balance for oil losses 40% can be attributed to oil sticking to the waste in the magnetic separator and oil flotation, and 20-30% via the strip surface, the rest in skimming leaks and exhaust. It is expected that these aspects will be improved significantly. Moreover, as tramp oils are not present, it is expected to incur less waste treatment costs (if the iron fines are clean, they can be easier used in scrap processing). The oil rejecting properties and the lower viscosity of the OFL compared to conventional oils allow an effective skimming of tramps and avoidance of lubricant and valuable tribological constituent losses, resulting in a significant reduction of lubricant losses, which could possibly reduce overall lubricant consumption by up to 50%. The resulting cleaner lubricant suggests improved productivity and higher product quality. Due to the more efficient cleaning process of the lubricant circulation system, the environmental impact (e. g. disposal of lubricant) is lower. Finally, the stability of the OFLs against degradation was shown to be higher1, leading to a longer use time and to lower costs and lower environmental impact.

Using the aluminum industry as an inspiration for a transfer of OFLs into steel cold rolling one can envision the achievements that are possible. Industrial experiences from the aluminum wire rod process using OFLs report about a reduced material and lubricant costs by about 50% after two years of OFL practice. Plant downtime and scrap quotas could be reduced significantly (claims appr. minus

60%). It has been possible to verify a low consumption of chemicals with the new OFL concept at an aluminum breakdown mill8. Less than 25% of active material has been used as compared to losses observed with oil emulsions and volatiles in the air have been reduced by 95%.

Considering these facts based on experiences gained from former projects1,8 and industrial practice on the aluminum rolling process it can be concluded, that under the condition of well-adjusted OFLs to the requirements of the cold rolling process comparable cost savings are very likely. Extensive industrial rolling tests are necessary for further adaptation of the lubricant to the specifics of the steel cold rolling process. For this, an adaptation of the lubricant is an absolute prerequisite before performing pilot trials and finally industrial cold rolling tests in this Pilot & Demonstration project.

This will lead to a significant reduction in costs for OFL consumption, maintenance, care and disposal by estimated 50%. The iron fines will be no oily, resulting in a significant 50% reduction in lubricant consumption per kg steel rolled. The filtration will be more efficient (no oily and sticky fines). More efficient filtration methods can be achieved with the OFL in comparison to the current auto backflush filters which are ineffective due to blinding, causing excessive backflushing waste during rolling applying o/w emulsion. Less defects are expected from roll marks - less roll changes – less grinding of work rolls by 10% - saving CO_2 and costs.

Process improvements, cost reductions and meeting further increasing environmental and regulatory requirements are the main drivers for the introduction of this innovative lubrication.

The incentives for the use of OFLs in steel cold rolling are very obvious:

- OFLs are environmentally friendly;
- online lubricant monitoring for OFL;
- facilitated care steps (simplifying the separation of tramp oils and particles with the OFLs);
- higher effective maintenance and disposal processes resulting into lower costs.

4.3 Challenges

There following relevant challenges must be overcome to implement OFLs as the new industrial standard lubricant for cold rolling:

- **OFLs do not provide the necessary lubrication performance and process compatibility for cold rolling of steel** The tribological functionality of OFLs differs extremely from those of standard oil-containing emulsions, which is strongly depending to the oil phase of conventional lubricants. In order to use those innovative lubricants in steel cold rolling, it will be necessary to adapt both, the lubricant chemistry itself as well as the rolling parameters.
- **The use of OFLs is not economical** As oils used for cold rolling emulsions are usually lower in costs the use of OFLs might be initially more expensive. Viewed overall, by the advantages in usage lifetime, care and maintenance effort, as well as by facilitations in the following process steps, the costs will be balanced.

4.4 Compliance with the "do no significant harm" principle

RollOilFree II is compliant with the 'Do No Significant Harm Principle' since it does not affect negatively any of the six environmental objectives of Article 17 of the EU Taxonomy Regulation 2020/852. In fact, as one aim of the project is to substitute environmentally critical lubricant ingredients e.g. palm oil, RollOilFree II will positively contribute to (c) the sustainable use and protection of water and marine resources; (d) the circular economy, including waste prevention and recycling; (f) the protection and restoration of biodiversity and ecosystems.

4.5 National or international research and innovation activities

Research on the substitution of o/w lubricants by OFLs (such as polyalkylene glycols – PAG) has been done in the projects *RollOilFree*, *LUBWORK*[7] and *Ambi 2013*[8]. The wear and lubrication important properties of the mentioned glycol-based synthetic lubricant were defined and tested within pilot rolling and semi-industrial trials in *LUBWORK*. Their basic feasibility for cold rolling of steel could be proven in both, *LUBWORK* and *RollOilFree*. Industrial application of OFLs is described for aluminium rolling only.

Nevertheless, the transfer into the steel cold rolling up to now is not done. In both projects the exceptional advantages regarding environment, production cost savings with respect to chemicals consumption and substantial improvement in terms of their handling (maintenance, care, disposal) are proven. Further improvements are claimed with respect to the hydrodynamic lubrication regime of the formulations as a mean to handle critical tribological conditions. With the necessity to evaluate long-term behaviour of the OFLs together with their interaction with plant components, extensive industrial trials are mandatory to be able to do the next step into the industrial application of OFLs regarding the steel cold rolling process. Errore. L'origine riferimento non è stata trovata. presents the E uropean projects *RollOilFree*, *LUBWORK* and *Ambi 2013* more in details.

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[7] RFSR-CT-2008-00011: Increase of cold rolling performance by new lubricant and innovative work roll concepts EUR 25861 (31/12/2011)

[8] Eurostars Cut-Off 10; Reference Number: 8390; Ambi 2013: Finalized development of a new type of oil free aqueous metal rolling lubricants (30/04/2017)

Table 2. Overview of key messages and timelines of the dissemination activities.

Name	Specific actions developed
RFCS-2015-709504: Steel cold rolling with aqueous oil-free lubricants (**RollOilFree**) (30/06/2020)	*RollOilFree* is the preliminary project on which this research proposal is based. It is focused on the elaboration of a concept for cold rolling with oil-free lubricants (OFLs) as substitute to the conventional oil-based lubricants in steel cold rolling. During a first pilot cold rolling trial it was successfully proven to reach the final strip thickness with comparable roll forces and strip temperatures. The laboratory long-term stability of the OFLs revealed excellent characteristics. Neither alteration of OFLs regarding a possible corrosive potential on installations nor impairment of the OFL lubrication profile could be observed. The expenditure for maintenance and care were considered reduced and therefore be regarded as advantageous in comparison to common oil/water (o/w) emulsions. Switching from o/w emulsions to OFLs is considered feasible with manageable effort. Beside necessary process engineering efforts also the lubricant monitoring needs to be adapted.
RFSR-CT-2008-00011: Increase of cold rolling performance by new lubricant and innovative work roll concepts (**LUBWORK**) EUR 25861 (31/12/2011)	*LUBWORK* deals with the development of different compositions of water-soluble lubricants for steel cold rolling and aluminium hot rolling. First pilot tests for steel cold rolling showed good performances in comparison to conventional lubricants. The tests with very thin strip thicknesses resulted in no sufficient process stability. Furthermore, a long-term stability under industrial conditions was not evaluated.
Eurostars Cut-Off 10; Reference Number: 8390; **Ambi 2013**: Finalized development of a new type of oil free aqueous metal rolling lubricants (30/04/2017)	Aim of the project was to optimise a new type of aqueous, mineral oil free lubricant coolants for metal rolling and to communicate their advantages to the market. The work was performed with respect to aluminium hot rolling as well as stainless steel cold rolling. The high potential in terms of improvements in environmental standards, fire safety and production cost savings with respect to chemicals of up to 70% are claimed. The volatility in the air has been reduced by 95% at an aluminium breakdown mill. The promising results are reported for aluminium rolling which is in line with the project results of *RollOilFree*. The main focus of the optimisation efforts was to further improve reduction capacity of the new lubricants, to enhance the hydrodynamic lubrication regime of the formulations as a mean to handle critical tribological conditions caused by the impact of rolling speed, reduction force and temperatures of the lubrication zone.

4.6 Interdisciplinary approach and integration of social science and humanities.

In order to provide a feasible solution for the successful transfer of OFLs into cold rolling of steel, an interdisciplinary approach is required and inevitable (see **Figure 12**).

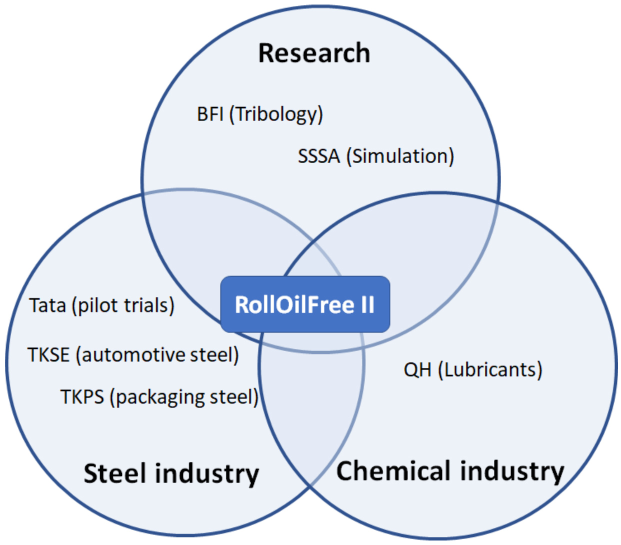

Figure 12. Interdisciplinary approach of the project.

Experts from the three steel industry companies and from one chemical company will collaborate with researcher from two institutes to find viable solutions and overcome obstacles. Expertise from several domains such as material science, tribology, forming technology, process management, chemistry and simulation will be needed to successfully carry out the tasks of this project.

Concepts from social sciences and humanities such as knowledge and information management will be applied to compile guidelines for a robust support for the transfer of OFLs into steel industry in the most concise and clear way possible. That is important, because only if the knowledge barriers for the implementation of OFLs are as low as possible and the communication of the benefits is clear, the widespread distribution of OFLs will be feasible.

5. Impact

5.1 Relation to the RFCS call

The project contributes to the following articles of the RFCS Regulation[9]:

Article 8 (d) maintenance and reliability of steel production tools and Article 10 (b) treatment of waste and recovery of valuable secondary raw materials, including slags, inside and outside the steel plant.

By implementation of OFLs for the steel cold rolling process, the lubricant care will be facilitated. Separation of tramp oils and wear debris will be easier and lubricant losses will be reduced. This will lead to a higher productivity, a decrease of downtime and will have a positive impact on the reliability of the cold rolling mill. Furthermore, the increased process stability will result in smoother surface qualities.

Article 10 (c) pollution control and protection of the environment in and around the workplace and the steel plant (gaseous, solid or liquid emissions, water management, noise, odours, dust, etc.)

The volatility of chemicals in the air has been reported to be reduced by 95% at an aluminium breakdown mill8. The same is to be expected in steel production which will significantly improve the environmental and health standards as well as fire safety. Furthermore, due to the more efficient cleaning process, the environmental impact (e.g. disposal of lubricant) is lower. It is expected that the OFL have a better long-term stability in comparison to the current oil-based emulsion lubricant which leads to lower costs and reduced environmental impact. High costs savings are expected thanks to the reduction of lubricant consumption and the effective care and wastewater treatment. Especially the cleaning procedure of the tank system will be improved which will lead to lower costs and enhanced HSE (Health, Safety and Environment). Furthermore, lower temperature (resulting in lower CO_2 emissions) and less cleaners are also needed for the easy wash off in the cleaning lines to reduce the drag-out of OFL by the strip surface compared to oil-based lubricants.

(f) life cycle assessment and life cycle thinking concerning steel production and use

Although the costs of OFLs are higher than the current o/w lubricants, thanks to the advantages mentioned above (maintenance costs reduction, disposal reduced, less scraps, lower energy consumption leading to decrease of CO_2 emissions and lubricant environmentally friendly), the using of OFL will lead to a lower TCO (Total Cost of Ownership).

[9] 'RFCS Regulation' - Council Decision of 29 April 2008 2008/376/EC amended by the Council Decision (EU) 2017/955 of 29 May 2017 and Council Decision (EU) 2021/1094 of 28 June 2021 (OJ L 130, 20.5.2008, p. 7)

5.2 Contribution to the Green Deal communication's elements

The proposed project contributes to the Green Deal communication's elements by the modernisation of steel sector. It is expected that the amount of OFLs needed for steel strip production will be reduced in comparison to the current amount of oil-based emulsion. The lower effort for the maintenance, care and disposal steps will also ensure a significant improvement in resources and environment efficiency. All these effects will lead to a reduction of the energy consumption and therefore lower CO2 emissions.

From the point of view of thermal recycling of waste skimmed oils, an extrapolation of the tonnage of the industrial partners results in approx. 707.714 tonnes of oil per year for the entire European steel industry. Assuming the ratio of 3,16 tons CO2 per ton oil during thermal recycling, this corresponds to an annual CO2 emission of approx. 2.236.377 tonnes. It is assumed that OFLs minimise these emissions. This calculation will be part of RollOilFree II.

The main benefits for the steel industries are the improvement of strip quality with the improved surface cleanliness, the simplification of lubricant care and the better wastewater treatment which lead to less energy consumption and lower CO2 emission.

In addition, the objective of minimising the risk of deforestation and forest degradation associated with products placed on the EU market was included in the Commission Work Programme 2021 concerning biodiversity and toxic-free environment. The substitution of palm oil as a lubricant component in cold rolling will help to reduce the number of new palm oil plantations and the deforestation of rainforests.

This project will demonstrate the possibility of a future steel production that is efficient, sustainable and green.

5.3 Project's contribution to the expected outcomes and impacts

The direct target groups of this project will be steel producers with cold rolling mills and producers of industrial process fluids, especially metal working lubricants. It is therefore not surprising that the industry partners of this consortium come from precisely these target groups:

TKPS represents the manufacturing of packaging steels (production of tin coated or electrolytic chromium coated steels), TKSE is a major European integrated steel producer, and the focus will be given in this project on two automotive steels. Tata will also be part of this project with its pilot plant which verify the technical interest and ensure the possibility to transfer the results to its rolling mill. Finally, QH as a global leader in industrial process fluids will give the possibility to adapt and improve OFL for the cold rolling steel industry.

With the participation of these companies, RollOilFree II confirms the technical interest and ensure the transferability of results in steel as well as in other metal industries, and so would strengthen the European steel producers market position and would allow for a know-how advance. **Table 3** presents the expected industrial benefits.

Table 3. Industrial benefits.

Benefit	KPI	Aim
Steel producers		
Increase of plant efficiency	Plant down time [h]	minus 60%
	Scrap quota [to]	minus 60%
Simplification of lubricant handling	Costs for maintenance/care/disposal [€/a]	minus 50%
Reduction of lubricant/ process fluid related costs	Lubricant costs [€/a]	minus 50% after 2 years
	Lubricant losses [to/a]	minus 50%
	Necessary dumping amounts [m^3/week]	minus 50 - 75%
Reduction of peripherical costs	Costs for work roll grinding [€/a]	minus 10%
	Costs for following processes (e.g. strip cleaning) [€/a]	minus 30%
Lubricant producers		
Product portfolio enlargement	Number of new products for steel industry	5 OFLs for steel cold rolling
Exploration of a new market segment	European steel cold rolling mills supplied with OFLs	20% of European cold rolling mills in 5 years

Beyond those direct target groups there is the potential of creating even more target groups by further spreading this lubricant into different technology sectors. This project generates knowledge about the necessary adaptions for a successful transfer of a lubricant originally designed for aluminium industry into steel industry. By using this knowledge there is the potential of an easy distribution on OFLs into other metal working industries, such as zinc or copper. That would support more industry sectors in getting on their way towards a greener and more sustainable production.

List of figures

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List of acronyms and abbreviations

Acronym	Full name
BFI	VDEh-Betriebsforschungsinstitut GmbH
HSE	Health, Safety and Environment
MMCR	Mathematical Model of Cold Rolling
OFL	Oil Free Lubricant
PAG	Poly-Alkylene Glycol
QH	Quaker Houghton
RBMT	Roll Bite Mimicking Test
SSSA	Scuola Superiore Sant'Anna
Tata	Tata Steel Netherlands B.V.
TCO	Total Cost of Ownership
TKPS	Thyssenkrupp Rasselstein GmbH
TKSE	Thyssenkrupp Steel Europe AG