Publishable Synthesis Report

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Potential Strategies for Reducing Particulate Emission During Dry Machining

Project Coordinator:
Fraunhofer Institut für Produktionstechnologie IPT

Partners:
Mikromat Werkzeugmaschinen GmbH & Co. KG
Richard Lloyd Ltd
Hecker & Krosch GmbH & Co. KG

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Summary page

Keywords:
environmental production, safety at work, cast iron, dry machining, particulate emissions

Dry machining operations conducted on metallic materials is associated with the release of fine and ultra-fine particles as well as with the production of geometrically defined chips. In contrast to the chips emanating from wet machining operations, these are not entrained in a liquid medium and removed. No systematic investigations have yet been carried out into the production mechanisms and characteristics of these process emissions. Against this background, the objective of this project, was to characterise the particle emissions released in dry machining operations conducted on metallic materials, based on the example of milling operations involving cast iron materials. In particular, relevant active correlations between process variables and emission parameters were to be identified and in-process approaches to influencing the nature and volume of particles released, were to be outlined in the following. The starting point for the investigations was a qualitative analysis of chip and particle production. The quantities which influence the emissions produced in dry machining operations were identified. In accordance with the declared objective of identifying process control approaches which can be adopted within the process, the investigation focused on variables whose changes are largely independent of facility and machine-specific parameters. This qualitative analysis was followed by an experimental characterisation of the particle emissions which occur in dry machining operations conducted on cast iron materials. Due to the complexity of the subject matter, it is particularly important to adopt a systematic approach to the planning, execution and evaluation of the experimental test series. Principles and instruments of the Design of Experiment technique were therefore used within the framework of the investigations in industrial practice. The particle fractions and concentrations were measured using gravimetrical and photometrical measuring techniques and particle analyses was carried out in the laboratory. The particle morphology were additionally analysed using microscopy. The effective interrelationships between factors which influence the machining process and relevant targets was investigated using statistical methods on the basis of the characterisation of the particle emissions. These steps formed the basis for an assessment of the particle emissions and an evaluation of their effects.

2
The Consortium

Due to the extent and complexity of the tasks outlined above, the work cannot be carried out by any one, individual company. It is, therefore envisaged, that, in order to accomplish the task in question, a project consortium will be formed which consists of

- a materials processing company
- a machine manufacturing company and
- a machine tool manufacturing company

The involvement of these industrial partners will ensure both that all activities are user-oriented and that the results are transferred efficiently to industry. It is also envisaged, that in view both of the machining tests required and of the questions to be addressed in terms of particle emis-sions, an institute which specialises in manufacturing technologies should be invited to join the consortium. The R&D provider selected, has the expertise in dry machining and in the measure-ment of particulate emissions during machining operations and the appropriate technical facilities.

The individual participants and their roles within the project are described in the following:

Mikromat Werkzeugmaschinenfabrik GmbH & Co. KG (Partner No. A1)
Mikromat Werkzeugmaschinen GmbH & Co. KG
Dr.-Ing. Christian Otto
Leiter Produktmanagement
Niedersedlitzer Strasse 37
01239 Dresden
Germany

Brief company profile and areas of expertise:
Mikromat Werkzeugmaschinenfabrik GmbH is a german company with a tradition of more than 130 years in the sector of design and production of high-precision machines. Today, the products of Mikromat are drilling machines, milling machines and grinding machines for high-precisions operations and HSC-operations. All products are CNC-machines and are available in various sizes as well as stages of automisation. The usage of the machines of the V HSC-

milling series allows a reduction of the machining time of steel and cast iron of up to 50%. The products are sold worldwide, with customers mainly in the automobile and automotive sector.

Role of the partner company:
Mikromat Werkzeugmaschinenfabrik GmbH will contribute to the project planned in terms of identification of dry milling potentials (cast iron), planning and execution of machining trials, identification of post-operational measures for reducing emissions as well as execution of comparative measures to evaluate different measures. The focus of Mikromat Werkzeugmaschinenfabrik GmbH contributions is on tasks 1, 2, 4 and 5.

Richard Lloyd Ltd. (Partner No. A2)
Richard Lloyd Limited
Mr Nathan Paxton
Director, Engineering and Sales
Cromwell Works Tenbury Wells
Worcestershire WR15 8LF
United Kingdom

Brief profile and areas of expertise:
Richard Lloyd Ltd. (Core Group Proposer), situated in Tenbury Wells, United Kingdom, designs and manufactures precision quality taps in the „Gold Cut“ high performance standard range and application specific high performance special taps to suit demanding engineering requirements. The company also designs and manufactures milling cutters for special applications to meet high volume outputs and unique situations where job specific milling is required. All modern requirements for Tungsten Carbide, PCB, and CBN cutting are addressed, together with the requirement for high speed and lightweight milling.

Role of the partner company:
Richard Lloyd Ltd. will provide consultancy on the topic of tool technology, provide experimental tools and attend / assess the machining trials. Thus Richard Lloyd Ltd. mainly contributes to tasks 1, 2 and 5.

Hecker & Krosch GmbH & Co. KG (Partner No. A3)
Hecker & Krosch GmbH & Co. KG
Herr Michael Krosch
Aachener Strasse 100
53909 Zülpich
Germany

Brief profile and areas of expertise:
Hecker & Krosch (Core Group Proposer) is a German company and a member of the Aachen Chamber of Industry and Commerce. The company is active in cast iron machining and metal machining in general. Its range of services includes parts design, part production, and the production of special-purpose parts or machine modules. The company was founded in 1969 as a repair and assembly shop. Today, more than 70 people work for Hecke & Krosch and an affiliated engineering service. Environmental engineering projects have been a part of Hecker & Krosch's services since 1990. The company managed to contribute towards protecting the environment through the further development of recycling processes for plastics.

Role of the partner company:
Hecke & Kroch GmbH & Co. KG will contribute the perspective of a material machining company to the investigations. Thus the focus of the activities is in tasks 1 and 5.

Fraunhofer IPT (Partner No. C1)

Fraunhofer Institute for Production Technology IPT
Dr.-Ing. Volker Sinhoff
Steinbachstrasse 17
52072 Aachen
Germany

Brief profile and areas of expertise:
The Fraunhofer-Institut für Produktionstechnologie IPT, whose mission it is to conduct industry-oriented specialised research and development, was established in 1980. The services provided by the Institute include the development and optimisation of technological solutions for manufacturing companies. It safeguards the competitiveness of its customers by ensuring that their expertise is always one step ahead of that of their competitors. Customers and collaborators come from all areas of manufacturing industry, particularly from the automotive industry and its suppliers, the precision engineering and optical industries as well as from the aerospace industry. Approximately 300 staff are currently engaged in on-going projects at the IPT. Particular emphasis is placed on student education and training. The Institute has facilities extending over an area of 6000qm, including 3500qm for laboratories and machine shops. Staff at the Fraunhofer IPT plan and design environmentally-oriented manufacturing facilities and non-company-specific environment management systems, on behalf of their customers. The range of services offered extends from measuring dust emissions in dry machining operations through resource-oriented optimisation of manufacturing processes and computer-assisted ecology-oriented product evaluation to the execution of comprehensive environment audits.

Role of the R&D-Partner:
The Fraunhofer IPT (R&D provider) will assume responsibility for project co-ordination. In rela-tion to the investigations planned, the main areas of activity will be to carry out experi-

ments, to apply measuring techniques to record particle emissions, to evaluate the results and identify potential approaches to solutions and optimisation.

3
Technical achievements

The use of cooling lubricants in metal machining operations, has been the subject of much controversy in recent years. It is generally agreed, that the possible advantages of wet machining must be weighed up against the considerable technical and economic cost. The cost involved in the procurement of the cooling lubricants themselves as well as the cost of facilities, personnel and energy, involved in the use, maintenance and disposal of the media, can be clearly allocated and evaluated in financial terms. Empirical investigations confirm that account must additionally be taken of the safety at work factor in wet machining operations. Recent forecasts assume that between twenty and sixty percent of all cutting operations will be conducted in dry mode in the medium to long term.

In comparison with the relative ease with which the economic advantages of dry machining can be calculated, any attempt to quantify the effects of this technique on the environment immediately runs into difficulties. One of the negative phenomena of dry machining operations, is the production of ultra-small chip particles, which are no longer entrained by a liquid medium and transported away during the machining operation. The release of dust emissions has been observed, particularly when materials which have brittle machining characteristics are concerned. Only a few investigations have taken place into the mechanisms which cause these emissions and the characteristics of these emissions. It was not possible to draw on any empirical data collected from extensive industrial implementation of the dry machining technique.

Against this background, the aim of this project was to characterise the particulate emissions produced in milling operations conducted on cast iron materials, as representative of dry machining operations involving brittle metallic materials and to identify relevant active correlations between process variables and emission characteristics. The results obtained, were used as a basis on which to evaluate the damage which can potentially be caused by the emissions released, and various approaches to emission control were discussed.

The investigations were initiated by systematically defining the influencing factors which result in the development of emissions in particle form. The influence exerted by the factors material, tool and cutting data were examined in detail on the basis of an analysis of discontinuous chip formation in machining operations carried out on cast iron using a defined cutting edge. As regards the material, ductile yield has a particularly pronounced effect on the type of chip produced. In relation to the cutting tool, both the tool angle and the effective cutting angle are particularly important. It is also important to give due consideration to the cutting data feed per tooth, cutting depth and speed.

The particles released when cast iron materials GG25 and GGG40 are milled, were characterised extensively on the basis of the qualitative analysis. In accordance with this objective, machining tests were duly carried out as part of a multi-factor test plan. The progression of the mass concentrations with time, grain size distribution of all of the particles produced as well as the shape and material composition of the individual particles were investigated.

The grain size analysis revealed that all of the groups are polydisperse systems with a mass-related distribution density showing only one maximum. Machining operations conducted on cast iron with laminar graphite, resulted in a higher proportion of dust-type particles than operations involving spheroidal graphite cast iron. Whilst approximately one third of the total particle mass consists of dust particles when GG25 is machined, the corresponding proportion when GGG40 is machined, is only around one tenth of this value. Like the grain size analysis, there was evidence that the material involved, has considerable influence on the inhalable thoracal and alveolar mass concentrations recorded. Here too, the peak values measured were considerably higher in operations conducted on GG25. Measurements recorded in the course of investigations showed that when the workpiece subsurface is machined, the concentration values are higher than when the core material is involved. A characteristic progression in the concentration over time, was also detected in milling operations conducted on both materials. Various particle geometries, depending on the particle size, were recorded for each of the materials. Coarse particles corresponded in shape to the characteristic chip forms produced. Below a certain grain size, only individual particles are detectable. The larger of these particles are individual chip segments. In addition to these, considerably smaller particles are also produced (sub-chip range). The shapes of the chip segments can be described as needle or sheet like. As the grain size diminishes, the proportion of isometric particles rises. An analysis of the structure of the dust particles also showed that the two-phase structure which is characteristic of cast iron, remains intact throughout the machining process. Consequently, there is no change in material characteristics as a result of this predominantly mechanical load. In contrast, the occurrence of spherical particles was observed when there was an excessive increase in the energy introduced via sufficiently small particles, due to high cutting speeds and large feed levels. This is attributable to melting and solidification of material.

As to the evaluation of all measurements performed the results concerning analysis of particle size, concentration as well as partcile morphology are the following:

Grain size analysis

All of the groups of particles investigated, were polydisperse systems with a uni-modal mass-related dispersion density. Machining operations conducted on lamellar cast iron is always characterised by a high level of dust-like particles. The average median mass diameter during machining operations conducted on GG25 is 674 µm and 1705 µm in those involving GGG40. When GGG40 and GG25 are machined, the proportions of particles released which have a grain size below 500 µm and which can therefore be described as dust-like, are 3.5 % and 33 % respectively.

Particle concentration

Like the grain size analysis, it emerged from the concentration analysis that the type of material involved, exerts considerable influence on the respirable thorax and alveolar mass concentrations measured. In milling operations conducted on GG25, the peak values recorded for the respirable fraction were 213 mg/m^3 and 40.6 mg/m^3 for the alveolar fraction. The corresponding values for operations involving GGG40 were 129.9 mg/m^3 and. 12.5 mg/m^3. The mean concentrations measured were between 50 and 70% lower for both materials. It was also established that there is a characteristic progression of the concentration over time. Higher emission levels are recorded when the workpiece subsurface is machined.

Particle shape

The particle shapes recorded when both of the materials were machined, varied in dependence with particle size. Whilst particles with the characteristic macroscopic chip form are detectable in grain sizes above 250 µm in the case of spheroidal graphite cast iron and above 500 µm in that of lamellar cast iron, only isolated particles are detectable below these limit values. The larger particles in this group are individual chip segments but much smaller particles (sub chip size) are also in evidence. Below a grain size of approx. 250 µm, steep increases are recorded in the proportion of needle-shaped particles for the GG25 material and in the proportion of plate-like particles for GGG40. In the case of all of the materials under investigation, dust particles smaller than 71 µm were found to have a predominantly isometric or plate-like shape.

The measurement results obtained from the grain size analysis and the concentration measurements, were evaluated using statistical techniques. It was established, that the mass proportions of the sieve fraction under examination, are influenced particularly by the parameters feed per tooth and cutting depth; highly significant effects were recorded for each of these factors when the effective direction was negative. The volume of larger particles produced, is also influenced to a considerable degree by the volume of larger particles produced. A clear correlation between the three factors listed and the median mass diameter of the group of particles under examination, was likewise confirmed. The values recorded for the mean and maximum mass concentrations are clearly dependent on cutting speed. In contrast, the influence exerted by the feed per tooth and the cutting depth on the mass concentration, can be ignored. The significance of the cutting edge angle in relation to the nature and volume of emissions released, is always low. Overall, it can therefore be concluded that the volume of dust particles produced, increases with diminishing feed values and cutting depths; higher cutting speeds also result in an increase in the proportion of dust and in higher average and maximum mass concentrations. The latter correlation must be regarded as critical, particularly in view of the increase in high-speed machining. A summary of the significant influences of the factors cutting speed, feed per tooth, cutting depth and cutting edge angle on the investigated output-values is given in **Fig. 1**.

After the emissions had been characterised, the impact of these emissions was evaluated. In relation to material goods, it is important to bear in mind that cast iron dusts are deposited in machines and electrical facilities and can cause damage as a result of their electrical conductivity and heat insulating properties. Additionally, the latent danger resulting from increased machine tool wear caused by the abrasive particles of cast material must be borne in mind. In contrast, the risk of direct although brief danger as a result of a dust explosion can be ruled out on the basis of the maximum mass concentrations, which were determined using metrological techniques in milling operations; the occurrence of dust fires is unlikely, provided the machine is kept reasonably clean. Work hygiene investigations show that the direct effects of the cast iron dusts under examination, have only low-level specific danger potential. However, the dust mass concentrations measured throughout the process, in the direct vicinity of the machining point, exceeded the legally permissible workplace concentration levels several times over; this applies particularly to the inhalable fraction. It can therefore be concluded that measures must be implemented which will permit the relevant limits set by industrial medicine legislation to be observed. If these relatively low concentration limits are fulfilled, it is likely that damage to goods as a result of dust will likewise be reduced.

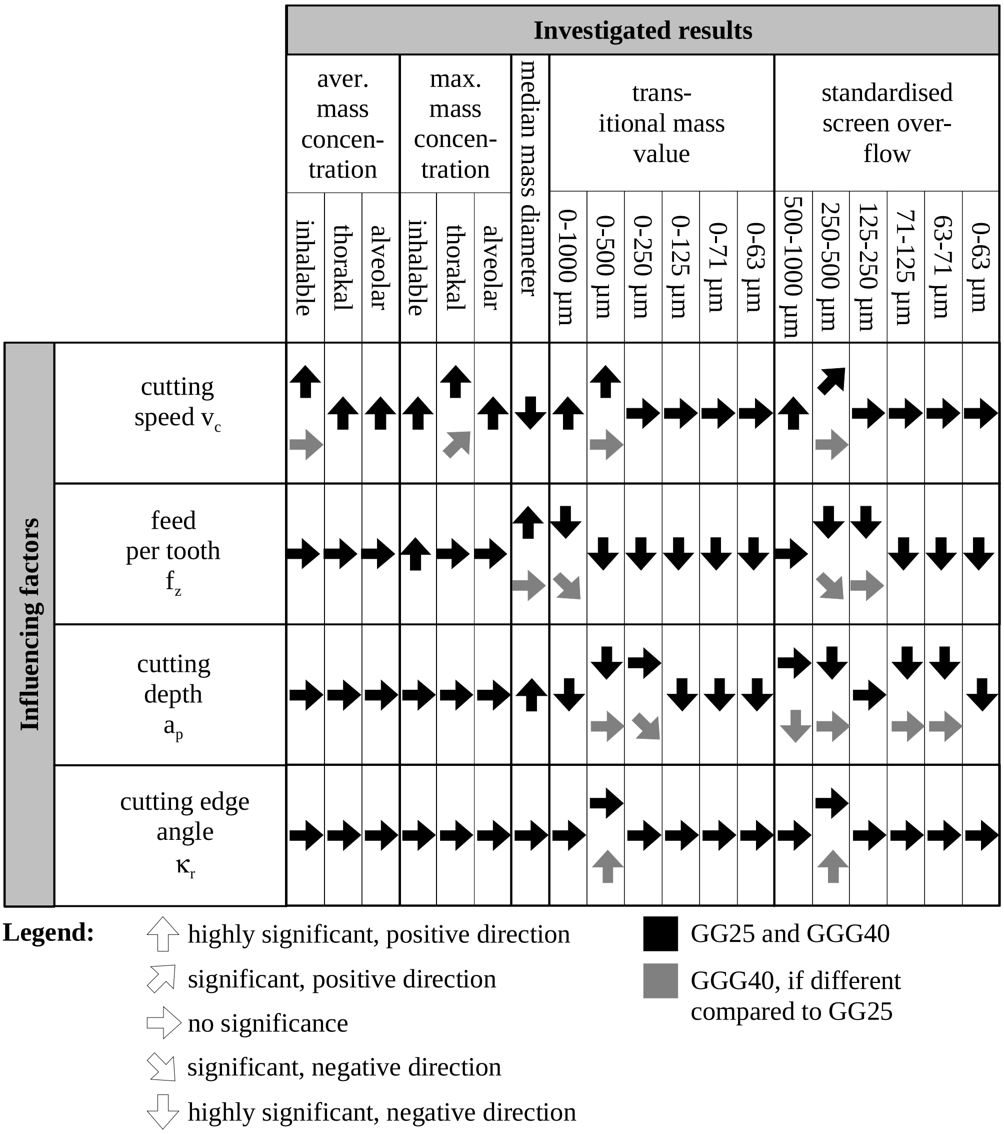

Fig. 1: Effects of different parameters on particle size and mass concentration and directions of effects

Various approaches to emission control were subsequently investigated on the basis of the negative effects recorded, which result from the release of casting dust. The parameters were first optimised using the steepest incline method with a view to minimising the mass concentrations. The peak concentration was reduced to one quarter of the maximum value within the parameter range under examination, simply by varying the two most powerful factors. As the tests showed, any attempt to bring about a significant reduction in concentration values involves drastic changes in the cutting data, which cannot be reconciled with the technical and economic demands to be met by the machining process. The options for emission-oriented parameter optimisation must therefore be regarded as existent, yet limited. In analogy to other areas of industry, in which liquid agents have been used successfully to suppress emissions, investigations were carried out in order to establish the degree to which the volume of dust produced in machining operations conducted on cast materials can be reduced by the use of minimum coolant levels. However, it was established that the introduction of an oil aerosol into a dust system consisting of cast iron particles, results not in an agglomeration of solid and liquid particles, but in an increase in the level of inhalable concentrations. The limit values currently in force in industrial medicine can therefore only be observed when additional measures are in place downstream. From the range of extraction and filter facilities currently used, compete encapsulation of the working area and a two-stage separation of the materials which do not belong in the air are recommended for the machining process and group of particles under examination.

Overall, the particle emissions which occur in dry milling operations, have been characterised thoroughly using the example of cast iron materials and relevant influencing factors have been identified. The underlying metrological and methodological approaches can be used as a basis for similar investigations into other machining techniques and materials. In view of the foreseeable extensive application of dry machining techniques in future, the results presented, will contribute to the integrative development of this technique, taking account of technical, economic and environmental effects.

4
Exploitation and follow-up action

It is envisaged that the results obtained in the course of the project will be used in two different dimensions:

- Direct use of the project results by the participating partners
- Dissemination of results beyond the project consortium

Both of these planned ways of exploitation or dissemination will be described more detailed in the following.

Direct use of the project results by the project partners

The consortium consists of a machine manufacturer (Mikromat Werkzeugmaschinen GmbH, prime proposer), a machine tool manufacturer (Richard Lloyd Ltd), a material processing company (Hecker & Krosch GmbH & Co. KG) and a R&D-Partner (Fraunhofer IPT, coordinator). Each of the SMEs involved stands to gain a specific advantage:

Machine manufacturer:
Dry machining of metals is gaining importance in industrial production. Therefore the request for machine tools for dry machining is rising, too. The project results will provide data which can be used for the design of machines for dry machining operations. In addition, the effectiveness of new and existing measures for reducing or collecting emissions will be investigated. This will contribute to the design of new products of Mikromat Werkzeugmaschinen GmbH.

Machine tool manufacturer:
The development of new materials as well as machines with a higher performance lead to a need for further development of cutting tools. The results of the project planned relating to the influence exerted by process parameters and, in particular, by the tool specification (geome-

try, cutting material) will provide data which can be used to optimise cutting tools for dry machining operations. This will contribute to the development of new cutting tools specially designed for dry machining operations and thus enlarge the range of products for Richard Lloyd Ltd. .

Material processing company:
Cooling lubricants have become a substantial factor within the framework of industrial production. Dry machining thus means a significant economic advantage for metal machining companies. The project results will provide data which can be used for the implementation of a low-emission dry machining strategy. The findings reached, in relation to potential integrated and downstream solutions will assist the conversion of existent manufacturing facilities to dry machining. This will increase safety at work as well as provide the companies with an economic advantage resulting from the reduction and prevention of environmental related costs.

The industrial companies involved, will thus benefit in terms of expertise and from a competitive point of view in the field of dry machining. The institute concerned will benefit in the following way:

R&D-partner:
The institute concerned will extend its areas of expertise. Environmental aspects of industrial production techiques are becoming an ever greater challenge. The search for clean technologies as a substitute for production techniques that are characterised by significant emissions or waste production thus needs systematic R&D mactivities as a basis for environmental improvements in industrial production. The results of the planned project will contribute to the expertise of the Fraunhofer IPT in the area of particulate emissions during dry machining (characterisation of emissions as well as identification and evaluation of potential precautionary and post-operational measures. The results will contribute to the follow-up investigation on the emissions related to other materials (e.g. other metals, ceramics, plastics) as well as other machining techniques (e.g. drilling, grinding, milling).

To this end, the R&D provider (Fraunhofer IPT) will document all relevant project results in the form of a final technical report.

Dissemination of project results beyond the project consortium

In addition to this, the results obtained in the project will be disseminated via the partners in-volved:

Transfer via industrial partners:
Cutting processes, both with a defined and with an undefined cutting edge, are key opera-tions in mechanical engineering Europe-wide. The trend toward dry machining can be detec-ted in most European branches such as automotive and consumer goods industry. As a result there is a significant need and a high potential for the transfer of the project results or experti-se gathered to other companies and branches. The indus-trial partners can contribute to this transfer by using their contacts to customers and suppliers in their business and geographic environment. Thus the project and the solutions identified can be used by a larger number of companies affected all over Europe.

Transfer via R&D provider:
At the end of the project the scientific results will be compiled into a final report by the R&D-partner. This will be the basis for effective use and further development of the project results by the participating SMEs. To disseminate of the results to other companies affected by dry machining emissions it is envisaged to write a manage-ment guideline in addition to the final report. This guideline will contain information about the general approach in terms of charac-terisation and possible ways to reduce particulate emissions during dry machining. Thus the transfer of the results to other materials as well as machining techniques (e.g. drilling, turning) will be ensured. In addition to that, follow-up projects in the sector of particulate emissions measure-ment in industrial production processes as well as investigations on innovative and ef-fective measures for emission reduction are envisaged to be initiated based on the project results by the R&D-partner. Possible industrial partners for those follow-up projects will be other European SMEs who have already worked with the R&D-partner.

Overall, it is thus guaranteed that the results of the project will be disseminated both among the project partners and beyond.

5
References

This publishable synthesis report contains only a brief description of the technical achievements. An explicit description of the scientific and technical results of the project is given in the final technical report. This report also comprises a documentation of all references.

6
Collaboration sought

The results should be interesting for all industrial companies that are working in the same sector as the industrial partners of the project. Apart from that the approach of investigation represents a basis for the investigation of particulate emissions resulting from other mechanical cutting processes or other materials cut. Especially the design of experiments methods and instruments have proofed to be valuable within the evaluation of the measurements results.