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Energy Efficient Process Chains for the Production of Powertrains

Berend Denkena, Marc-André Dittrich, Maik Bergmeier, Miriam Handrup, Kolja Meyer, Laura Onken*, Christopher Schmidt

Institute of Production Engineering and Machine Tools, An der Universität, 30823 Garbsen, Germany

Abstract

Mobility is one of the major drivers of greenhouse gas emissions (GHG). The project *Powertrain 2025* addresses this issue through the optimization of selected powertrain components in terms of friction, weight and service life to achieve savings in GHG during use. Energy efficient process chains and improved tool concepts enable this optimization. As a result, significant increases in energy efficiency can be achieved both in production and in usage of the powertrain components. A holistic, environmental evaluation, which visualizes optimization potentials and enables energy and resource efficient production control, completes this work.

Keywords: environmental evaluation; microstructuring; deep rolling; process chain control; tool concept

1. Introduction

Individual transportation is becoming increasingly popular, especially in emerging countries due to growing population [1]. This trend is accompanied by energy intensive production and high emission operation of passenger cars. In the EU greenhouse gas (GHG) emissions from passenger cars accounted for 11% of total GHG emissions in 2016, with ascending values [2]. In view of the impending climate change, it is therefore of utmost importance to reduce emissions during the production and operation of passenger cars. The project *Powertrain 2025* addresses this issue, which should enable weight savings of 2.5 kg, a reduction of 7% of GHG emissions during operation by friction optimization and a 20% decrease of the manufacturing energy demand through the optimization of specially selected components during production and operation. The selected components are cylinder liner, profile shaft, intermediate shaft and vane pump in the steering system, which are optimized via new production processes, like microstructuring,

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* Corresponding author. Tel.: +49-511-762-18211; fax: +49-511-762-5115.
E-mail address: onken@ifw.uni-hannover.de

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deep rolling and new hybrid tool concepts, see Fig. 1. Furthermore, an approach is developed, which combines economic and environmental target values for detailed planning and production control in order to reduce resource and energy demand during production and to enable an evaluation of process chains in regard of production time, waste, resource and energy demand.

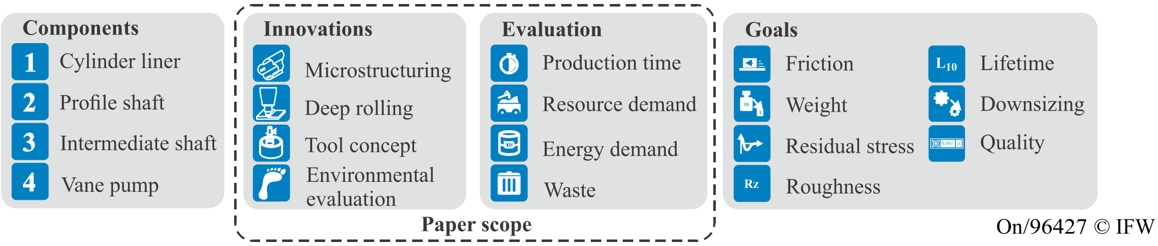

Fig. 1. Project overview and paper structure.

This paper focuses on the presentation of innovative process chains including microstructuring and deep rolling as well as the description of the new hybrid tool concept, which combines microstructuring and non-circular turning. These innovations are evaluated using a new evaluation approach, which is based on the overall energy demand of process chains. An integration of this approach into detailed planning and production control enables the comparison of old and innovative process chains as well as process chain design according to a minimum energy demand.

2. Noncircular turning and microstructuring of cylinder liners

In order to reduce fuel consumption and emissions of passenger cars with internal combustion engines, the automotive industry is developing smaller engines, leading to an increase in power density. This is accompanied by increasing mechanical and thermal demands on engine components [3]. Still, fuel and oil consumption also depend on the inner friction within the powertrain. Therefore, various approaches have been made for further reduction of fuel and oil consumption, such as improving the friction between piston and cylinder liner by means such as honing, coatings and microstructured surfaces [4–7]. It was shown, that the application of micro dimples to the inner surface of cylinder liners can reduce fuel consumption by 4.5% [6, 8, 9]. In addition, the oil consumption was reduced by 70 – 80% and the engine wear was lowered by 50% [10].

For the manufacturing of micro dimples in cylinder liners, laser material ablation is often used because of its flexibility in terms of the size and distance of the micro dimples. A disadvantage is the low material removal rate of 0.005 mm^3/s – 0.16 mm^3/s. Another method is machining of micro dimples with cutting inserts. Therefore, Denkena et al. introduced a single-toothed cutting tool, which used a support bearing to lean against the workpiece surface. This guarantees a defined distance between cutting edge and surface and therefore a constant depth of cut despite possible improper form or position of the workpiece [11]. In order to increase the productivity of microstructuring processes, hybrid tools with an active actuated cutting edge combined with standard honing tools, that were developed in [12, 13], can be used. Due to the active deflection of the tool cutting edge via piezo actuators, a maximum radial deflection of 22 µm at structuring frequencies of 2,500 Hz was achieved [12]. Given a structuring rate of 2,500 Hz the productivity is 25 times faster compared to the fly cutting process and up to 6 times faster compared to laser structuring. The actively controlled cutting edge also makes it possible to manufacture different patterns of micro dimples within one cylinder liner. Besides microstructuring, an additional approach for a reduction of internal friction is to compensate the mechanically or thermally induced distortions in combustion engines that occur during the engine run and lead to piston jam [14]. The geometric distortion of a cylinder liner can also occur in axial direction. Free form honing with actively controlled honing stones is used to produce the negative distortion shape, as shown in Fig. 2 in order to compensate the geometrical distortion [15, 16].

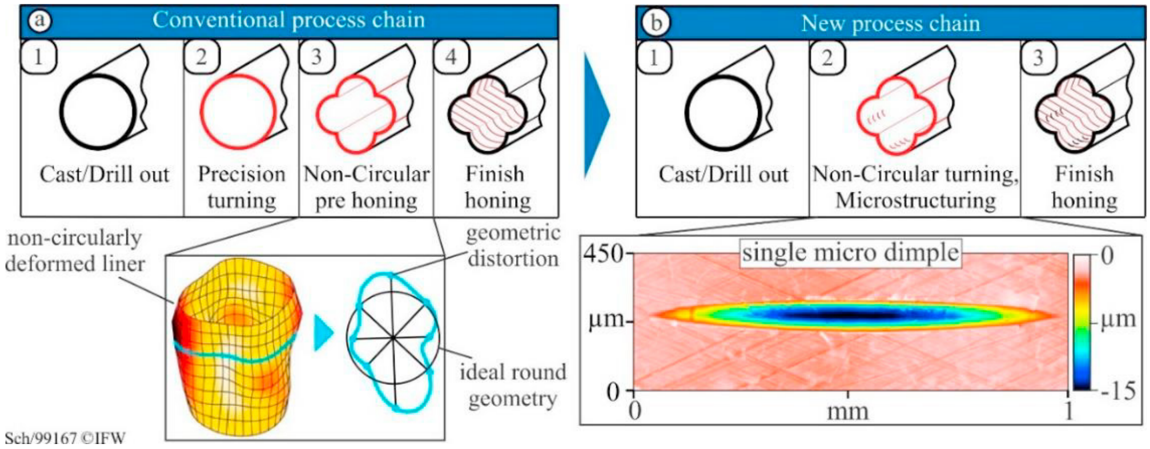

Fig. 2. Process chain for the manufacturing of non-circular and microstructured cylinder liners

2.1. Process chain for manufacturing of cylinder liners

However, in the current process chain (Fig. 2a) there are two honing steps which are associated with a very high honing oil requirement. This has a negative effect on the energy balance of the production process due to the additional provision and preparation by auxiliary units. Within the project *Powertrain 2025* the two major focuses are the products' resource-conserving period of use and the manufacturing process (Fig. 2b). Therefore micro dimples are machined for friction reduction in the engine's period of use. Within the manufacturing process, the energy-intensive rough-honing is substituted by turning.

Concerning the production of cylinder liners, one of the main objectives are energy savings through the substitution of non-linear honing by a non-linear spindle process. In contrast to honing processes, turning processes can be performed without cooling lubricant and the occurring honing sludge. Furthermore, for the first time non-circular cylinder liners will be combined with machined microstructures to further reduce internal friction in the engine. Both processes are individually available today, but have not yet been combined in a single tool. Consequently, their interaction has not yet been investigated and therefore the challenges of their combination are not known in detail. As the two processes are not only combined, but also integrated into the process chain, their effect on the following finish honing process needs to be investigated as well.

In order to meet the requirements of the process chain for energy efficient manufacturing, a new tool has to be developed for combining non-circular turning and microstructuring. The new tool is designed for turning and will consist of two modules. One module will be used for turning and the other will be used for microstructuring the workpiece. Due to the combination of the two processes into a single tool, clamping errors between these two

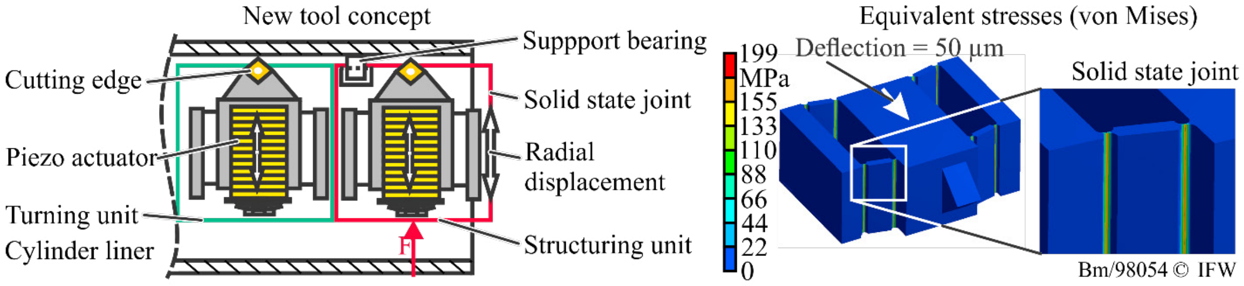

Fig. 3. Tool concept with two structuring units. Piezo actuator guided by a solid state joint for non-circular turning and structuring unit.

manufacturing steps are eliminated. Both modules have active piezo-actuated cutting inserts with a limited stroke of ~50 µm and the cutting edges are guided by solid state joints in a trapezoidal arrangement (Fig. 3).

The first module is fixed to the tool and allows the tool to generate non-circularity in the precision turning process. The second module for the downstream microstructuring process of the inner cylinder surface is mounted on radially aligned guide rails. A support bearing guides the entire module, which is pushed against the workpiece's inner wall by a hydraulic cylinder. This enables the module to follow the non-circular cylinder wall and the limited travel of the active cutting edge can be completely used for the depth of the micro dimples. Concerning the process's dynamic, frequencies of up to 250 Hz are sufficient to achieve the necessary cutting speeds of v_c = 500 – 1,500 m/min for non-circular turning. However, the frequency of 2,000 Hz represents the physical limit of the structuring unit and therefore limits the productivity. Next, first tests concerning the cutting behavior are conducted with a drilling rod in order to perform analogy tests for the precision boring that will later be performed by the combined tool. During these experiments, the process forces will be measured in order to anticipate the required static and dynamic stiffness that the combination tool will have to provide. Using these results in combination with the presented tool concept, it is possible for the first time to manufacture non-circular cylinder liners with micro dimples.

3. Heat treatment substitution during the axle tap manufacturing

The optimization of manufacturing process chains bears a high potential to fulfill the project aim. Besides the energy consumption during production, the production of replacement parts is also energy intensive, which is why the service life is also important. Therefore, the goal of an optimization lies not only in the optimization of resource consumption and the number of required manufacturing processes, but also in the optimization of component service life. The geometry, the material properties and the applied thermal and mechanical load decisively determine the lifespan of a component. If the applied load exceeds the material-specific characteristic properties, the component fails. For example, notches and diameter changes can have a negative influence on the load resistance, as these lead to increasing load stresses [17]. To improve the lifespan, heat treatments to harden the material have been established. While the results of heat treatment on steel are predictable to a high degree, the disadvantage is a high energy demand for the austenitization and the need of fluid quenching media. Heat treatments also cause distortions of the end geometry of the component. Therefore, additional cutting processes of hardened material are necessary in order to fulfil the requirements for shape and position tolerances. These finishing processes are both energy- and cost-intensive due to increased tool wear and lower productivity in comparison to the machining of soft material. In order to avoid heat treatments, surface integrity-altering processes can be used. The surface integrity is a combination of factors involving the surface topography and the surface-near metallurgy [18–20]. Besides the hardness, another key element for the lifespan is the residual stress state. Here, compressive residual stresses have been proven to be beneficial for the typical load cases [18]. Manufacturing processes that increase the surface and subsurface hardness and induce compressive residual stresses are deep rolling or roller burnishing [21]. During both processes, a ceramic or carbide tool is pressed against the surface of the workpiece. In roller burnishing, the force is applied by a spring and the tool is usually cylindrical. In deep rolling, the force is applied hydrostatically, and the tool is usually spherical. However, the potential for the increase in hardness depends strongly on the material properties and the process parameters.

If the hardening through those processes is not sufficient and, thus, the heat treatment is irreplaceable, hard machining could be avoided in order to reduce the energy demand of the process chain. Therefore, it is necessary to carry out both, roughing and finishing processes on soft material. In order to comply with the manufacturing tolerances, the occurring distortions of the end geometry through heat treatment have to be compensated beforehand. This approach has been followed by [22] during the machining of bearing cages. Since the quality of the components depends strongly on the interactions between the machining and heat treatment, both processes should be continuously monitored and controlled together to use interactions between processes [23]. For the machining of bearing cages, a process chain control was developed which controls the geometry of the machined components across all processes by adapting of the process parameters. Because the geometry is the system output of the control loop, it has to be known to calculate the geometry error. Thus, an inline measurement after the soft machining and an end of line measurement after the heat treatment are necessary. With a process chain control, the defects can be minimized and thus the energy efficiency of the process chain increases. Besides a process control, many monitoring approaches were investigated recently in order to maximize the process reliability and the efficiency of processes [24, 25].

3.1. Process chain for the energy efficient manufacturing of axle taps

To achieve this a reduction of energy consumption during manufacturing, both previous introduced methods are applied to the process chain for the manufacturing of the axle tap to illustrate the energy saving potential of a process chain adaption exemplary. The axle tap can be used as an example for the future of drive train components, because it is used in both, combustion and electricity driven vehicles. Currently, the parts are quenched and tempered using induction and a tempering process in an oven on two areas of the workpiece. The current methods enables a high reproducibility and a high productivity on the one hand but also has the necessity for additional units. Both areas are indicated in Fig. 4. One area is on the contact position between the axle tap and the wheel bearing.

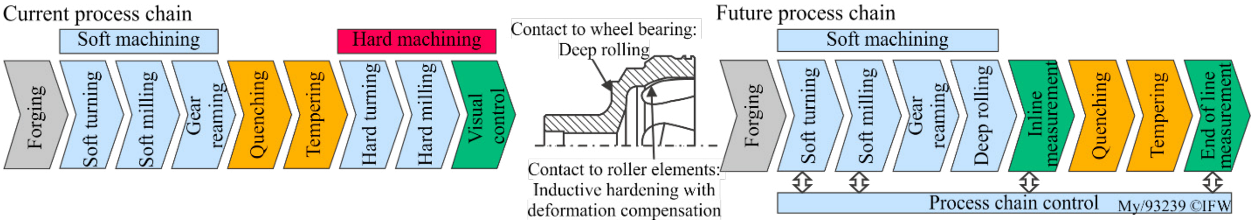

Fig. 4. Process chain for the energy efficient manufacturing of axle-taps

Here, the axle tap is primarily subjected to static loading. The failure mechanism consists of a seizure of both components. The other position is the ball raceway. Here, a dynamic load is applied due to the movement of the wheels. The current process chain consists of separated soft machining prior to and hard machining after the heat treatment. The two options for the reduction of the heat treatment and hard machining processes are adapted to the load on the respective position. It is known from the literature, that rolling processes induce a lower increase in hardness compared to heat treatments. Since there should be no relative movement between axle tap and wheel bearing, a mechanical hardening offers a high probability of sufficient hardness. The dynamic load on the ball raceway indicates the necessity of a thermal hardening process. Therefore, the future process chain aims to perform a heat treatment without subsequent hard machining. As described, a process chain control will be implemented which adapts the process parameter, so that the expected distortion of the heat treatment can be pre-compensated through the soft machining. By measuring the deformation using in- and end of line measurements, a feedback about the actual geometry can be provided and a control loop can be established.

3.2. Rolling induced hardness increment

Examining the possibility for a hardness increment on the contact area, forged axle tap blanks were deep rolled and roller burnished using ECOROLL HG6 and EG5 tools. The blanks are manufactured from AISI 1055 structural steel and in order to remove the forging influenced surface, a turning operation was performed. The blank material had an initial hardness of 247 ± 5.5 HV1. For these first experiments, the surface of the outer ring as opposed to the aimed radius area was machined The deep rolling experiments were carried out using two deep rolling pressures p_w = [400; 600] bar and two overlap factors u = [80; 90]%. The overlap is calculated by the relationship between the

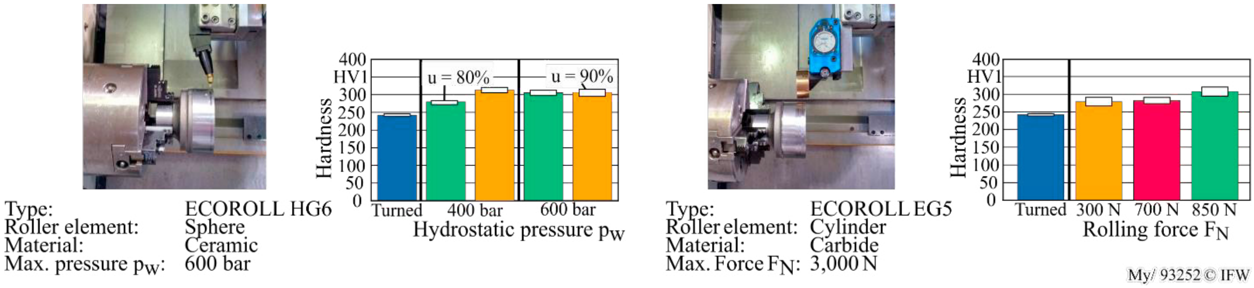

Fig. 5. Resulting hardness after deep rolling and roller burnishing of AISI1055 steel

Hertzian contact radius r_k and the feed f. The calculation of the overlap is described in [21]. The roller burnishing was performed using a constant feed of f = 0.08 mm and the force was varied in three stages F_N = [300; 700; 850] N. The forces were measured using a Kistler 9121 dynamometer.

Fig. 5 shows the machining setup and the resulting hardness after deep rolling. For the case of deep rolling, the highest hardness could be achieved using an overlap of u = 90% and a pressure p_w = 400 bar, where the hardness is increased to from 247 ± 5.5 to 308 ± 8.3 HV1. Using the same pressure with a lower overlap generates a lower hardness increase, because less deformation causes a lower cold hardening. A similar result could be achieved using the roller burnishing process. Here, it should however be noted, that the used forces were on the lower register of the maximal force. In order to increase the hardness, higher forces should be experimentally observed. The resulting hardness is lower than the hardness induced by quenching, which is around 450 HV1. Therefore, further experiments regarding a possible failure during the use stage should be performed.

4. Environmental evaluation

The newly developed process chains serve to reduce the energy requirement during the production and use of a car. To quantify this reduction, a method is required that enables process chains to be assessed environmentally based on their energy requirement. Current approaches focus on the product or individual processes [26-28]. The interactions between processes within process chains are not considered. This way, the current assessment approaches do not reveal the influence of the properties of the process chain, e.g. of its productivity, on the overall energy requirement of a product. In the following, an approach is presented, which links the energy demand of a product with the productivity of the process chain in one holistic indicator. This indicator is then integrated into detailed planning and production control.

4.1. Development of a holistic environmental indicator for process chain evaluation

The energy requirement of a product can be measured by the cumulative energy demand (CED). The CED considers all processes from raw material extraction to disposal of a product [29]. The energy demand for upstream processes E_{UP}, like the production and supply of cooling lubricants, the energy demand for the machining process itself E_{MP}, and downstream processes E_{DP}, like recycling and disposal of cooling lubricant and tool have to be considered. If several processes have to be taken into account, the energy demands can be totaled, s. Eq. 4.1:

$$CED_i = \sum_{i=1}^{m} E_{UP,i} + \sum_{i=1}^{n} E_{MP,i} + \sum_{i=1}^{p} E_{DP,i} \tag{4.1}$$

Eq. 4.1 provides information about the energy required to manufacture one product through various processes. However, interdependencies between the various processes, which are part of a process chain and result in its productivity, are not considered. Furthermore, several products are usually manufactured within a process chain. As a result, Eq. 4.1 is now linked to the productivity of the process chain and designed for the production of multiple products to enable a holistic evaluation. The linkage to productivity is based on capacity utilization and quality indicators in accordance with the overall equipment effectiveness (OEE) [30]. The scrap rate (*SR*) is selected as quality indicator, the capacity utilization is evaluated by the energy demand caused by idle times ($E_{I,i}$). By linking this indicators, a new key figure CED_{PPC} is generated, which indicates the energy requirement of a product averaged over a process chain with *n* processes and *m* manufactured products, s. Eq. 4.2:

$$CED_{PPC} = \frac{1}{m}\left((1+SR)\sum_{j=1}^{m}\left(\sum_{i=1}^{n} CED_{i,j} + \sum_{i=1}^{n} E_{I,i,j}\right)\right) \tag{4.2}$$

In case of an energy demand of 1.85 kWh per product, a scrap rate of 5% and downtimes of 10%, the application of the indicators results in an energy share of 11% percent caused by the process chains related effects, which are therefore not negligible.

4.2. Integration into detailed planning and production control

The CED_{PPC} can be reduced both with planning and controlling measures. Planning measures by detailed planning, such as the adjustment of process parameters, serve to reduce the CED_i. Controlling measures by production control, such as quality controls or set-up time reductions, serve to reduce *SR* and E_I and thus, maximize the productivity.

However, the systematic selection of the process parameters causes contrary effects. An increase of process parameters, e.g. through higher spindle speed or feed rate, minimizes process time. The energy requirement is reduced due to the base load of the machine. On the other side, tool wear increases and more coolant lubricant is required caused by higher temperatures. In turn, this leads to an increasing energy requirement by upstream and downstream processes. In addition, a negative influence on quality cannot be ruled out.

As can be seen, the mentioned measures in detailed planning and production control contradict each other and create a multi-criteria optimization problem, which cannot be solved manually. For this reason, the next step will be the development of a software solution that enables an automated detailed planning and production control. For this purpose, the mathematical relations will be mapped with the help of the software, interfaces to production will be set up and an algorithm will be developed that configures the process chain to achieve a minimum CED_{PPC}.

5. Summary and outlook

The reduction of the environmental impact is a major challenge nowadays. The contents of the project *Powertrain 2025* aim to solve this challenge by reducing the impact generated by the production and use of passenger cars. Therefore, novel production processes, tool concepts, production planning and control approaches were introduced. With the help of microstructuring and non-circular turning of cylinder liners, the inner friction of combustion engines will be reduced to lower fuel and oil consumption in combustion engine driven vehicles. The related new hybrid tool concepts leads to an energy efficient productive process chain and lower cooling lubricant consumption due to eliminating the pre-honing process. Mechanical finishing processes have the potential for the substitution of thermal treatments. If a heat treatment is indispensable, energy can be saved by removing the hard finish machining processes by the adaption of process chain controls, which adapt the parameters to minimize the quenching induced dimensional error. Detailed planning and production control according to the CED_{PPC} serve to evaluate the improvements achieved by the introduced processes and to adjust process chains under economic and environmental aspects. With completion of the project *Powertrain 2025* energy efficient process chains for the production of powertrains, which are optimized in terms of friction, weight and service life are developed.

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