Comparison of the Resource Efficiency of Alternative Process Chains for Surface Hardening

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Abstract

As negative implications of resource exploitation and further undesirable ecological developments, e.g. climate change, increase, companies are confronted with novel challenges. Especially during the production stage of a product's lifecycle companies have the possibility to influence the resource consumption by choosing the most efficient process chain for a certain manufacturing task. To compare accumulated resource flows of different process chains, a new valuation method using a resource efficiency index was developed. Exemplarily, this paper will analyze the resource consumption of two alternative process chains for surface hardening of a workpiece resembling a guide rail.

Keywords:

Production Planning; Sustainable Manufacturing; Machining

1 INTRODUCTION

Resources, e.g. raw materials, are getting scarce as a result of the rapidly rising demand. In order to prevent the negative implications of resource exploitation and further undesirable environmental developments, e.g. climate change, legislation is starting to restrict and influence both companies and consumers in their behavior. In addition, the image and consequently the competitiveness of a producing company are strongly influenced by its efforts regarding the establishment of resource efficient and sustainable products and processes [1]. These developments have led to the consideration of environmental effects of the usage and disposal phase of the product lifecycle during product design. But in most cases not only using and disposing of a product cause resource depletion and waste, but also the manufacturing phase can be held responsible for a large share of the environmental burden [2]. Therefore, it is important to consider the manufacturing process chain specific resource consumption during the production planning phase, as 80% of the environmental impact of a manufacturing system is fixed at that time [3]. In particular, if several alternative manufacturing process chains are able to fabricate the product a decision will have to be made. Apart from the decision criterion cost, the criterion resource efficiency should be taken into consideration for the reasons mentioned above. In spite of these findings, the resource flows of manufacturing processes are not as well known as they should be. Furthermore, research studies state that available methods supporting the evaluation of resource efficiency are still insufficient [4]. Main approaches that aim to quantify resource flows and to evaluate the resource efficiency of manufacturing process chains will be discussed shortly in the following.

Current approaches that aim to quantify resource flows of a manufacturing process either use a material and energy flow based analysis or attempt to derive resource consumption in a predominantly analytical way. Especially machining processes have been analyzed concerning the production of waste material, the consumption of cutting fluid and the use of energy [5, 6]. However, the quantification of resources used in the process is based solely on theoretical calculations, rendering the approach inept for the prediction of overall resource flows that include the manufacturing equipment as well. A variety of valuation methods utilizing an ex-post material and energy flow based analysis, also known as inventory analysis, exists. Most of these methods also include the assessment of the environmental impact of the regarded object [7, 8, 9]. The approaches mentioned above focus on an ex-post analysis, which does not show the predictive character needed in the production planning phase. Recently, a few approaches sought to develop a general method for resource efficiency evaluation [10, 11]. The goal of this paper is to further develop and apply a general method for evaluating resource efficiency of manufacturing process chains based on the approach introduced by [11]. Therefore two alternative process chains, one using only traditional manufacturing processes and one including a new hybrid manufacturing process, will be compared and their resource efficiency will be evaluated.

The remainder of this paper is set out as follows. The next section presents the modeling of the material and energy flows and the evaluation of the resource efficiency. The modeling procedure is then applied to two alternative process chains for surface hardening in the third section. Finally, the resource flows are calculated and the material and energy efficiency are determined for each process chain. Using the resulting resource efficiency index a quantitative comparison of the alternative process chains is possible.

2 METHODOLOGY

2.1 Modeling of Resource Flows

A manufacturing process chain consists of different manufacturing processes that are needed to change a product from one defined state to another. In this paper a manufacturing process is modeled as a composition of the manufacturing technology used, the manufacturing system the technology runs on and the additional peripheral systems. The manufacturing system and more complex peripheral systems can be subdivided into their components, which is indicated by the circles surrounding the manufacturing system in Figure 1.

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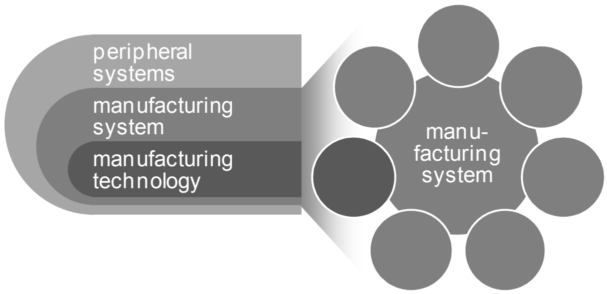

Figure 1: Manufacturing process model.

Generally every resource r_i can constitute an input $r_{i\ IN}$ and an output. Whereas output is divided into output going into the product $r_{i\ PROD}$ and output that is wasted $r_{i\ OUT}$. Input resources used in a cutting process are for example energy, material, water, auxiliary material, coolant etc. The quantity of every $r_{i\ IN}$, $r_{i\ PROD}$ and $r_{i\ OUT}$ required by the examined manufacturing process for one manufactured product can be described by corresponding resource vectors $\boldsymbol{r_{IN}}$, $\boldsymbol{r_{PROD}}$ and $\boldsymbol{r_{OUT}}$ (see Figure 2).

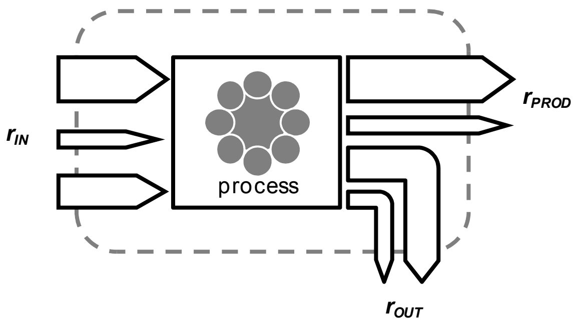

Figure 2: Resource flows of a manufacturing process.

In general resources used in manufacturing process chains can be divided into two main categories: material and energy. This subdivision of resources facilitates both the quantification of resource flows and the evaluation of resource efficiency. For the quantification of indirect resource flows (e.g. the proportion a manufacturing process has regarding the power consumption of a central compressed air system) the produced quantity per time unit is needed as supplemental information. The following subsections describe the quantification of $\boldsymbol{r_{IN}}$, $\boldsymbol{r_{PROD}}$ and $\boldsymbol{r_{OUT}}$ using the manufacturing process model.

Input Resource Flow Quantification

The input energy flow consists of the manufacturing system and the peripheral systems. The energy consumption of the technology is part of the manufacturing system. The required power can be calculated theoretically for many standard technologies. As the technology is executed on the manufacturing system, the theoretical value has to be multiplied with a correction factor due to interaction between technology and manufacturing system. Generally, the input energy flow of manufacturing systems and peripheral systems can be calculated using the power consumption of defined system states and the time during which the system is in one of the defined states based on the work schedule of the product. Accordingly, the input energy flow is set together as follows:

$$r_{EnergyIN} = r_{EnergyIN\ manufacturing\ system} + \sum_k r_{EnergyIN\ peripheral system k} \quad (1)$$

The power consumption of system states usually varies due to the composition of active and inactive components of the manufacturing system or peripheral system. Figure 3 shows the calculation of the power needed in the system states A to D depending on the system's active components.

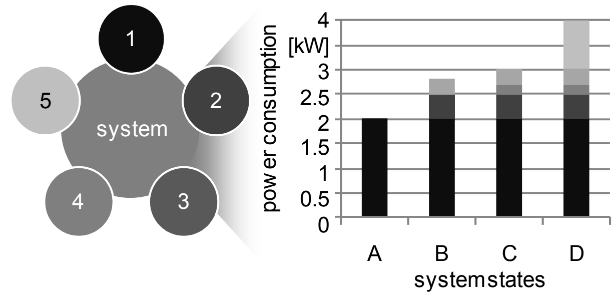

Figure 3: Power consumption of different system states.

For each defined state of a system the required power has to be assessed. The best way to determine the values is by conducting power measurements of the system. As the method should be applicable in the planning phase the power data has to be a requirement when soliciting a quotation. If there is no data available the required power values have to be estimated using measurement data of similar systems if possible. If only a fraction of the peripheral system's input energy flow can be assigned to the manufacturing process, the energy flow can usually be allocated to the manufacturing process based on the manufactured product quantity and relative energy intensity of the product.

The input material flow consists of all material going into the process. Generally there are there different categories of material used in manufacturing processes: workpiece materials, auxiliary materials and tool materials. The workpiece materials and some auxiliary materials can be directly allocated to the product. Other centrally provided auxiliary materials and tool materials can be allocated to the manufacturing process based on the manufactured product quantity and relative material intensity of the product.

Product and Output Resource Flow Quantification

The product energy flow is either the ideal energy used to perform a certain manufacturing process or the minimal energy of all the technologies in the alternative process chains that can be used to perform the process step. The product material flows equal all workpiece material flows and the auxiliary material flows that go into the product. Typically, the required workpiece material can be calculated using product design data.

The output energy and material flows are established by subtracting the product resource flows from the input resource flows. In the case of the workpiece, the output material flow is determined by subtracting the product geometry from the unmachined part geometry.

2.2 Resource Efficiency Evaluation

Resources are usually understood as natural resources subdivided into raw materials such as minerals, environmental media such as air, water or earth and flowing resources such as wind or solar energy [12, 13]. These categories already include most of the resources that are potentially used in a manufacturing process. In order to make the term even more practical for industrial application, resources such as electrical energy have to be integrated.

The term 'efficiency' is defined in various ways depending on the particular context. In general, efficiency can be understood as the ratio of benefit and effort. Relating this definition to resources either implies that, given a certain amount of resources used, the amount of produced units has to increase in order to obtain a more resource efficient situation. Or, on the other hand, the provided the amount of produced units is fixed and the amount of resources used has to be decreased. Whereas the use of resources includes contamination, damage and waste represented by $r_{i\,OUT}$.

In order to allow a resource efficiency calculation, all resources have to be standardized to one consistent unit. In this paper, the above-mentioned resource categories may be used. The unit for the category material is kilogram [kg], requiring the unification of solids, gases and liquids being substances in different states of aggregation. For the category energy the standard units are Joule [J] or kilowatt hours [kWh].

Having assessed the meaning of efficiency for manufacturing processes and eliminated the unit calculation problem, the material efficiency of a manufacturing process $\omega_{Material}$ is defined as follows [11]:

$$\omega_{Material} = \frac{\sum_{i=1}^{n} r_{i\,PROD}}{\sum_{i=1}^{n} r_{i\,IN} + \sum_{i=1}^{n} r_{i\,OUT}} \tag{2}$$

The benefit of a manufacturing process is the product resource flows and the effort put in which consists of the input resource flows and all output resource flows that do not go into the product. This definition implies that the more input flows directly into the product the higher the resource efficiency. Efficiency of 100% is only attained, if all resource input goes into the product itself, leaving no additional output. Also, the more auxiliary resources are needed for the process, the more the efficiency decreases. Consequently, resources that do not go into the product are accounted for twice in the denominator, representing an input resource on the one hand and waste or contamination on the other hand.

As the output energy flow has no know detrimental effect on the environment it does not have to be accounted for as effort. Accordingly, the energy efficiency of a manufacturing process ω_{Energy} can be reduced to:

$$\omega_{Energy} = \frac{\sum_{i=1}^{n} r_{i\,PROD}}{\sum_{i=1}^{n} r_{i\,IN}} \tag{3}$$

The resource efficiency is based on both material and energy efficiency. The ratio of material efficiency to energy efficiency may vary according to the company's focus. In this paper it is assumed that material and energy efficiency are equally important and the resource efficiency index is calculated as follows:

$$\omega_{Resource} = \frac{\omega_{Material} + \omega_{Energy}}{2} \tag{4}$$

3 APPLICATION

3.1 Alternative Process Chains

As application this paper analyzes the resource consumption of two alternative process chains for surface hardening of a workpiece resembling a guide rail. Both process chains start from the same semi-finished part, a bar with a square cross section (150 mm length, 28 mm width, 18 mm height) consisting of soft-annealed 100Cr6. The two alternative process chains both modify the workpiece by machining a 10 millimeter wide slot with a depth of 3.1 millimeter and realizing a hardened surface layer with a hardening depth of 0.4 millimeter as shown in Figure 4.

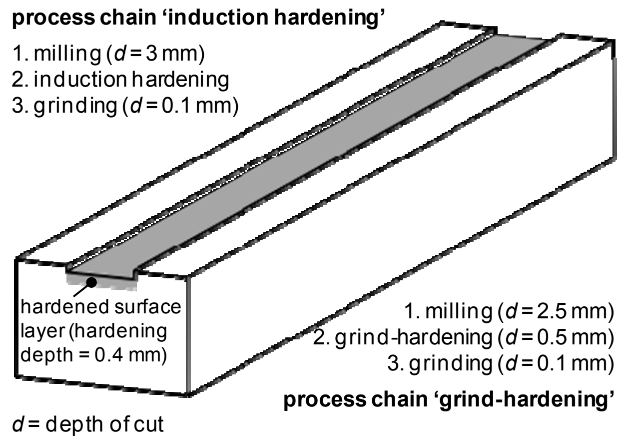

Figure 4: Alternative machining of workpiece.

The two alternative process chains, one using only traditional manufacturing processes and one including a new hybrid manufacturing process, is compared and their resource efficiency is evaluated. As shown in Figure 4 and Figure 5, the traditional process chain includes a milling process, an induction hardening process [14] and a grinding process. As customary, grinding is used as a finishing process after several steps of soft machining and a subsequent heat treatment at the end of the process chain.

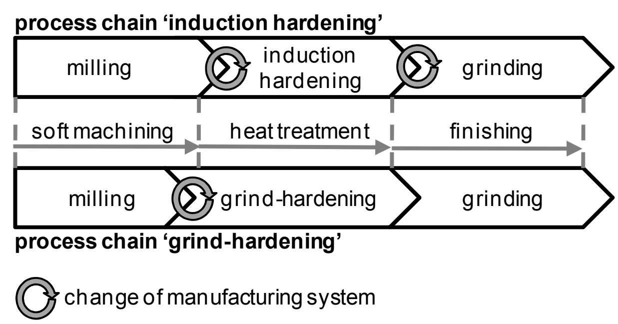

Figure 5: Comparison of the two alternative process chains and classification of the process steps concerning production phases.

The alternative process chain employs the "grind-hardening" process, which is an innovative approach to cut down the process and auxiliary time by substituting conventional hardening processes [15]. Therefore, grind-hardening is a hybrid manufacturing process, which can be classified as a soft machining and heat treatment process at the same time. Grind-hardening enables a process integrated heat treatment by grinding with subsequent finishing in one clamping. The large amount of heat in the contact zone between the grinding wheel and the workpiece, which is generated by deformation, shearing, friction and separation while grinding, is used for surface layer hardening by means of a short time austenization of the machined part. The martensitic hardening is mainly achieved by self quenching [16] supported by the convective heat transport of the used coolant [17].

3.2 Modeling of Resource Flows of the milling process

In the following, the different resource flows will be modeled exemplarily with the milling process (see Figure 6) of the grind-hardening process chain.

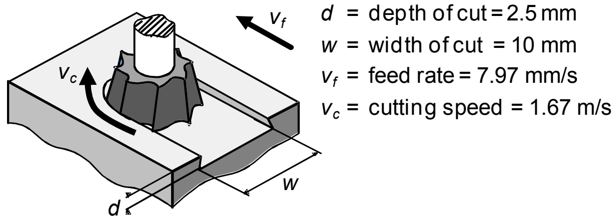

Figure 6: Face-milling process.

Firstly, the product **energy flow** is assessed. The power necessary for the process P_c can be determined by multiplying cutting force F_c and cutting speed v_c:

$$P_c = F_c \cdot v_c \tag{5}$$

König et al. [18] describe how the cutting force can be calculated theoretically, so that no previous measurements are required. In this case the cutting power is 894 Watt. The product energy flow results from multiplying power and cutting time t_c:

$$r_{EnergyPROD} = P_c \cdot t_c = 894\,W \cdot 18.9\,s = 16{,}896.6\,J \tag{6}$$

The input energy flow of the considered manufacturing system, the milling machine, can be derived from the different system states of the process as described in Section 2.1. Figure 7 shows the measured power of the milling process over time and visualizes the four states of the milling machine. The power graph displays the actual power measured on the one hand and the approximated power consumption on the other hand. The approximated power represents the ideal run of the power curve neglecting singular power peaks.

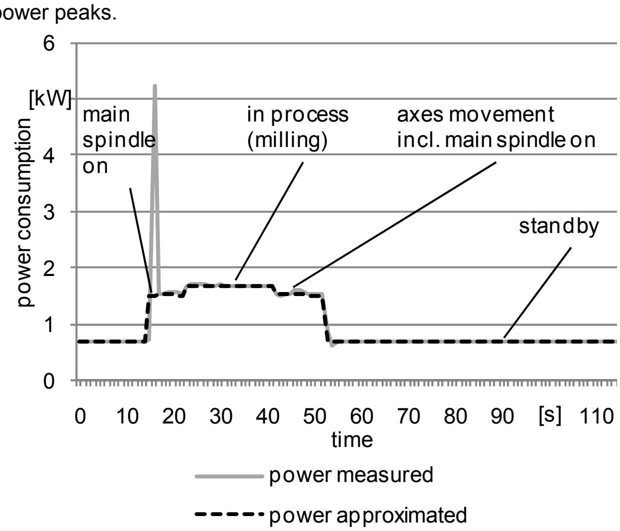

Figure 7: Measured power consumption of the milling process.

In order to variably model the milling process, the power consumption of the main components is assessed. As the machine's axes movement only occurs when the spindle is turned on, the power consumption of the axes movement has to by derived by subtracting the power consumption of the spindle from the measured value. With these component power values the resulting power consumption of the system states can be calculated independently, making further power measurements unnecessary. Only the power needed to execute the technology itself has to be assessed separately. When determining the technology power consumption it is again possible to calculate the power consumption independent of measurements by using the theoretical process power described in Equation 5 and multiplying the value with a correction factor, that has to be derived from empirical studies. These empirical studies include a variation of parameters and simultaneous measurement of the electrical power consumed. For the milling process considered in this paper a non-linear correlation of depth of cut and power consumption was ascertained concerning the correction factor. The discovered correlation is visualized in Figure 8.

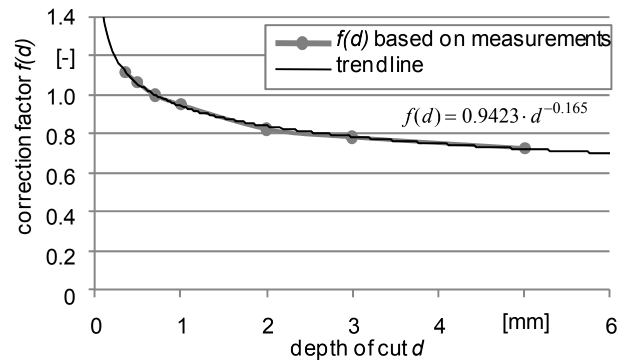

Figure 8: Correction factor of technology power consumption.

The grind-hardening process chain has a depth of cut of 2.5 millimeter and a correction factor of 0.810. Accordingly, the power consumption of the technology as one component of the manufacturing system is calculated as follows:

$$P_{c,real} = f(d) \cdot P_c = 0.810 \cdot 894\,W = 724.14\,W \tag{7}$$

On the basis of the now given information about the power consumption of the components, the different system states can be calculated as depicted in Figure 9. In this case, component 1 is not one physical consumer but subsumes all small components that consume power when the milling machine is turned on, including e.g. transformers or lighting.

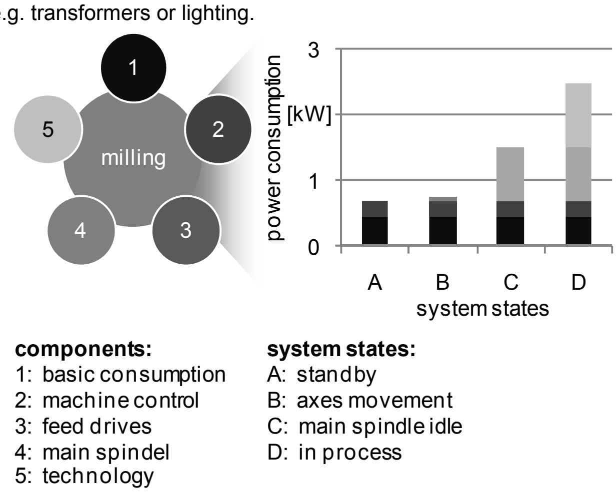

Figure 9: Power consumption of the states for the milling machine.

The input energy flow can be determined by multiplying the system states of the milling machine and the time during which the machine is in one of the defined states based on the work schedule for the milling process. The assumed waiting time is a result of the difference between process time and the cycle time of the production line. The energy for each process step and state is listed in Table 1 and the final input energy flow of the manufacturing system results in 138,816 Joule.

step	system state	time [s]	energy [J]
clamping	state A	60	42,000
machining	state B	7	5,250
	state C	3	4,500
	state D	18.9	42,036
	state C	3	4,500
	state B	7	5,250
unclamping	state A	20	14,000
cleaning	state A	10	7,000
waiting	state A	20.4	14,280
sum		**149.3**	**138,816**

Table 1: Work schedule of the milling machine.

The only peripheral system used during the milling process is the compressed air system. In this case, instead of modeling the entire system only the energy needed to produce the estimated amount of compressed air is calculated. Based on the machine that was examined and its work schedule the input energy flow of the peripheral system is determined for a compressed air consumption rate of 1.5 liters per second at 6 bar for 10 seconds (step ‘cleaning’ in Table 1). The resulting energy flow is 13,072 Joule. The entire input energy flow according to Equation 1 is:

$$
\begin{aligned}
r_{EnergyIN} &= r_{EnergyIN\,millingmachine} + r_{EnergyIN\,compressedair\,system} \\
&= 138{,}816\,J + 13{,}072\,J \\
&= 151{,}888\,J
\end{aligned}
$$

The input **material flow** of the workpiece corresponds to the semi-finished part of 0.5935 kilogram of soft-annealed 100Cr6. The product material flow is made up of 0.557 kilogram of 100Cr6 forming the machined workpiece. The output material flow is established by subtracting the product material flow from the input material flow resulting in 0.0365 kilogram. The milling tool material flow is an input and output flow but does not go into the product. Also the fraction of the milling tool, which is allocated to one workpiece results from distributing the entire tool material equally over the expected tool life.

The resource flows of the other processes can be modeled and assessed in a similar way. Especially, for the grinding processes the energy flows of the coolant system, as a complex peripheral system, are modeled using a state based approach as introduced above for entire manufacturing system. In addition, the coolant consumption per workpiece is calculated by dividing the entire coolant residing in the coolant system by the quantity of products that are machined during a coolant-renewal interval.

3.3 Resource Efficiency Evaluation

Having assessed all resource flows based on a weekly production quantity of 800 pieces, the resource efficiency of the alternative process chains can be determined. Table 2 shows the material flows of the induction hardening process chain. The material flows of the grind-hardening process chain are displayed in Table 3. Due to the fact that the semi-finished part and the final workpiece geometry are the same, the material flows are identical. The tool waste of the induction hardening process chain is less than the tool waste of the grind-hardening process chain, because the tool wear of grind-hardening is added. The coolant flow is independent of the utilization ratio of the grinding machine and therefore identical for both process chains. In this case a coolant system with a capacity of 800 liters of water based coolant solution and a coolant-renewal interval of 26 weeks are assumed.

	$r_{Material\ IN}$ [kg]	$r_{Material\ OUT}$ [kg]	$r_{Material\ PROD}$ [kg]
tool waste	0.0043	0.0043	0
workpiece	0.5935	0.0365	0.557
cooling water	0.05	0.05	0
coolant	0.0435	0.0435	0
sum	0.6913	0.1343	0.557

Table 2: Material flows of process chain ‘induction hardening’.

	$r_{Material\ IN}$ [kg]	$r_{Material\ OUT}$ [kg]	$r_{Material\ PROD}$ [kg]
tool waste	0.0143	0.0143	0
workpiece	0.5935	0.0365	0.557
coolant	0.0435	0.0435	0
sum	0.6513	0.0943	0.557

Table 3: Material flows of process chain ‘grind-hardening’.

In order to compare the energy efficiency of the two process chains a benchmark for each production phase has to be found. Table 4 displays the ideal energy flows concerning the three phases introduced in Figure 5, which will be used as the basis of comparison in the following evaluation. For the heat treatment phase the energy needed for the austenitization is applied, assuming a low heating rate [19]. Further, the minimal energy of the analyzed technologies is used for the soft machining and finishing phase.

production phases	energy [J]
soft machining	20,280
heat treatment	2,491
finishing	6,807
sum	29,578

Table 4: Ideal energy flow concerning the production phases.

In order to determine the input energy, Table 5 and Table 6 show the different process steps. Each step relates to the energy consumed by the corresponding manufacturing system and peripheral systems. The energy of all process steps added up finally forms the energy of the entire process chain. Before each change of manufacturing system and at the end of each process chain the workpiece is cleaned for ten seconds using the compressed air system. The additional cooling system in the induction hardening process step is needed for quenching the workpiece to realize surface hardening.

step	system	energy [J]
milling	milling machine	126,790
	compressed air	13,072
induction hardening	induction hardening machine	160,700
	cooling system	87,450
	compressed air	13,072
grinding	grinding machine	336,127
	coolant system	157,120
	compressed air	13,072
sum		907,403

Table 5: Input energy flow of process chain ‘induction hardening’.

The values concerning the milling process step in Table 6 are derived from the resource flows modeled in Section 3.2.

step	system	energy [J]
milling	milling machine	138,816
	compressed air	13,072
grind-hardening	grinding machine	348,450
	coolant system	158,400
grinding	grinding machine	168,577
	coolant system	98,400
	compressed air	13,072
sum		938,787

Table 6: Input energy flow of process chain 'grind-hardening'.

Applying Equation 2 to the calculated material flows (Table 2 and Table 3) the material efficiency of the process chains can be determined. The energy efficiency of each process chain is calculated by dividing the accumulated ideal energy by the entire input energy of the respective process chain as implied in Equation 3. The specific efficiencies of the different process chains are listed in Table 7. The resource efficiency is calculated according to Equation 4, indicating the grind-hardening process chain as the most resource efficient alternative.

	process chain 'induction hardening'	**process chain 'grind-hardening'**
material efficiency [%]	67.47	74.70
energy efficiency [%]	3.26	3.15
resource efficiency [%]	35.37	38.93

Table 7: Resource efficiency of both process chains.

4 SUMMARY AND OUTLOOK

This paper introduced an approach for evaluating the resource efficiency of manufacturing process chains. The procedure was applied to two alternative process chains for surface hardening. The material and energy flows of both chains were determined and evaluated – identifying the new hybrid manufacturing process 'grind-hardening' as a resource efficient alternative to the traditional hardening process using induction. Further analysis of possible transport and handling processes should be conducted to expand the scope of the process chain valuation. Furthermore a weighting scheme for resources has to be developed in order to reflect the special characteristics of different materials and energy types and their ecological effects.

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