Sustainable Materials and Technologies 34 (2022) e00509

Contents lists available at ScienceDirect

Sustainable Materials and Technologies

journal homepage: www.elsevier.com/locate/susmat

Alloy and process design of forging steels for better environmental performance

Wiebke Hagedorn [a,c,*], Alexander Gramlich [b], Kathrin Greiff [a], Ulrich Krupp [b]

[a] ANTS - Department of Anthropogenic Material Cycles, RWTH Aachen University, Wüllnerstraße 2, 52062 Aachen, Germany
[b] IEHK - Steel Institute, RWTH Aachen University, Intzestraße 1, 52072 Aachen, Germany
[c] Wuppertal Institute for Climate, Environment and Energy, Doeppersberg 19, 42103 Wuppertal, Germany

ARTICLE INFO

Keywords:
Steel
Material development
Environmental assessment
Product design
Lightweight solutions
Alloy

ABSTRACT

In material development processes, the question if a new alloy is more sustainable than the existing one becomes increasingly significant. Existing studies on metals and alloys show that their composition can make a difference regarding the environmental impact. In this case study, a recently developed air hardening forging steel is used to produce a U-bolt as an example component in automotive engineering. The production process is analyzed regarding the environmental performance and compared with the standard quench and tempering steels 42CrMo4 and 33MnCrB5–2. The analysis is based on results from applying the method of Life Cycle Assessment. First, the production process and the alterations on material, product, and process level are defined. The resulting process flows were quantified and attributed with the environmental impacts covering Carbon Footprint, Cumulative Energy Demand, and Material Footprint as they represent best the resource-, energy- and thus carbon-intensive steel industry. The results show that the development of the air hardening forging steel leads to a higher environmental impact compared to the reference alloys when the material level is considered. Otherwise, the new steel allows changes in manufacturing process, which is why an additional assessment on process level was conducted. It is seen that the air hardening forging steel has environmental savings as it enables skipping a heat treatment process. Superior material characteristics enable the application of lightweight design principles, which further increases the potential environmental savings. The present work shows that the question of the environmental impact does not end with analyzing the raw material only. Rather, the entire manufacturing process of a product must be considered. The case study also shows methodological questions regarding the specification of steel for alloying elements, processes in the metalworking industry and the data availability and quality in Life Cycle Assessment.

1. Introduction

Steel is one of the major metals and forms one of the biggest mass flows regarding the anthropogenic resource use. It provides input to various sectors and society in form of semi- and final products [1]. This goes along with enormous environmental impacts. In total, 7.2% of the global greenhouse gas emissions were directly attributed to the energy required for the iron and steel industry in 2016, in total 3.6 billion t CO_2 eq [2,3]. The Intergovernmental Panel on Climate Change (IPCC) demands halving global emissions by 2050, translating to 1 Gt CO_2 per year to combat climate change. It is known that a combination of energy and material efficiency measures applied to the steel industry is necessary to meet climate targets [3,10]. The concept of the circular economy offers solutions with aiming for an increased material efficiency, which “could weigh on steel demand growth” leading to a reduced steel production and environmental impact [8].

The steel industry has a long history of recycling, which is a core principle of the circular economy. It had considerable achievements in terms of environmental issues and resource scarcity. The production of steel from secondary sources requires up to 10 times less energy than producing steel by the primary route [4]. But the secondary route has its limits and there is no question that setting up a perfect recycling system is unrealistic [4]: The end-of-life (EoL) collection rate is <100%. Other materials entering the smelt contaminate the steel and losses as well as impurities result from the remaining imperfect alloy-specific sorting, recycling, and processing yields. It requires a continuous demand for

* Corresponding author at: ANTS - Department of Anthropogenic Material Cycles, RWTH Aachen University, Wüllnerstraße 2, 52062 Aachen, Germany.
E-mail address: wiebke.hagedorn@ants.rwth-aachen.de (W. Hagedorn).

https://doi.org/10.1016/j.susmat.2022.e00509
Received 21 September 2021; Received in revised form 2 September 2022; Accepted 16 October 2022
Available online 22 October 2022

primary material to compensate for dissipative losses and to adjust melts according to the required alloy composition due to downcycling effects and contaminants [4–6]. An important sector in terms of the steel input and example for a conflict area for recycling is the automotive industry. The treatment of vehicles at the EoL is a significant source of contaminants as, for example, stainless steel or copper wires cannot be separated completely. At the same time, their production requires high-quality steel [4]. Current studies based on cross-sectoral stock models show an increase of total steel demand despite the established recycling, which provides secondary material and with that substitutes primary resources [7]. Even though, there are still environmental saving potentials through improving the recycling system, it is not sufficient to address the climate targets and even meet steel demand in future [1].

Applying further material efficiency measures is highly product-centric [9]. Thus, estimations and extrapolations based on average values are difficult due to the variety of products and processes [10]. There is a high importance of individual case studies for final steel products as they can give valuable insights. Here, the material selection is also from high importance as it dictates the product's environmental profile directly and indirectly. The development process of alloys is crucial and more often related to the questions of sustainability. This concerns the material composition itself, but also the implications for manufacturing process and product design due to its inherent and targeted material characteristics, the resulting product performance, and its treatment at the EoL [11]. One focus should be set on the alloying elements, which form the main bottleneck when it comes to the steel supply [12,13]. Regarding the design of steel products, various technological, economic, and ecologic influencing factors must be considered, which are partly in conflict with each other [14].

Based on the given insights, the present work focuses on the assessment of the environmental performance of a forged product (U-bolt) in the automotive industry made from the new air-hardening ductile forging (AHD) steel. Here, the relation between the material development, the implications for the manufacturing process and product design are covered. To analyze the environmental performance, a Life Cycle Assessment (LCA) is carried out focusing on the Carbon Footprint (CF), Cumulative Energy Demand (CED), and Material Footprint (MF). The impact categories are chosen according to the ecologic hotspots of the steel industry as illustrated before. The technological data such as the chemical composition of the new and reference steels, mechanical properties, and information regarding the production process are taken from experimental data of the underlying research project, which are previously published [16,44].

The research questions are:

(1) Which technical and environmental effect has the change in alloy composition compared to the standard forging steel grades?
(2) How does the new developed alloy change the manufacturing process and product design?
(3) What effect has the new developed alloy on the environmental performance of the product?

The paper is structured as follows. First, the case study about the material development and product application is described. It covers the material characteristics as well as the production process of the U-bolt made from the newly developed and initial steel. The changes in process and product design due to the choice of alloy are explained. Then, the methodology of LCA is introduced including the proceeding. It covers the description of the goal and scope of the study and how the material composition, the production processes and product design were considered in the quantification. Afterwards, the results are outlined and discussed including a reflection on the applied methodology and identified gaps.

2. Methodology

2.1. Case study

Forged components for automotive application are largely made from steel alloys as these materials offer high mechanical properties accompanied by low production costs. In 2020 514.987 t of die forged products were produced in Germany, demonstrating the importance of the products for the automotive industry [15]. A case study of the industry initiative lightweightFORGING [16] demonstrated that forging products in a standard passenger car can contribute up to 48% of its weight. Therefore, the ecological impact of these components should be critically assessed regarding lightweight potentials.

Forging steels can be classified by the respective heat treatment, which is necessary to achieve the final mechanical properties. The two most common used types are the quench and tempered (Q + T) steels and the precipitation hardened ferritic-perlitic (PHFP) steels. The heat treatment of the Q + T steels, compare Fig. 1, consists of hot forging (normally between 900 °C–1250 °C), cooling to room-temperature, austenitization (heat-treatment above the austenite formation temperature Ac_3, dependent of the chemical composition, 750–900 °C for plain carbon steels), quenching to room-temperature in water or oil to form martensite and finally temper annealing (heat treatment beneath Ac_1, 723 °C). Several years ago, PHFP were developed with the aim to shorten the heat treatment. These steels get their final properties by a controlled cooling directly from the forging heat. By means of this shorter heat treatment, the process costs, energy demand and thus emissions were substantially reduced [60]. Additionally, internal stresses and the efforts for final machining are also reduced as the cooling conditions are more cautious than for the Q + T steels. But the balance of strength and impact toughness of the PHFH steels is far beneath the Q + T steels, which is why Q + T were not completely substituted and are still used for many applications.

To address this issue, the question arose if a steel can be developed which is processed by the short heat treatment of a PHFP steel but reaches the mechanical properties of Q + T steels. This was successfully implemented by the design of the AHD steels. These steels achieve a complete martensitic microstructure during air-cooling from the forging heat as displayed in Fig. 1 [17]. Martensitic transformation by air-cooling is achieved by a suppression of competing transformations like bainite or ferrite formation through the addition of alloying elements like manganese, molybdenum and boron [18]. The chemical composition of the new steel grade and the reference alloys are displayed in Table 1. The AHD steels have been developed in publicly funded projects in cooperation with the German Forging Association. First, new chemical compositions were designed based on thermodynamic equilibrium calculations and the literature and consecutively cast on the laboratory scale. The mechanical properties of the steels were comprehensively characterized, and the chemical composition adjusted accordingly in an iterative manner. Finally, the laboratory results have been tested by a large-scale industrial trial, where 50 t of the steel were melted in an electric arc furnace (EAF) and casted via ingot casting. The newly developed steel class reaches comparable mechanical properties with an air-cooling after forging like the reference Q + T steels 33MnCrB5–2 and 42CrMo4. The properties of the new steel grade were investigated on the laboratory [17] and the industrial scale [19]. Different components from U-bolts weighing 2 kg to planet carriers of a planetary gear weighing 250 kg were forged and the mechanical properties were compared to the components made from the reference alloys. While the larger reference components were produced from 42CrMo4, the U-bolts were produced from 33MnCrB5–2. In this study, the environmental impact of all three alloys was assessed with the U-bolt as the use case. As reported previously [19], strength and ductility of the investigated materials reach similar levels as the reference alloys, while the fatigue strength was increased by 129%. This increase in fatigue strength enables future lightweight optimization, as the component design is shifted from static

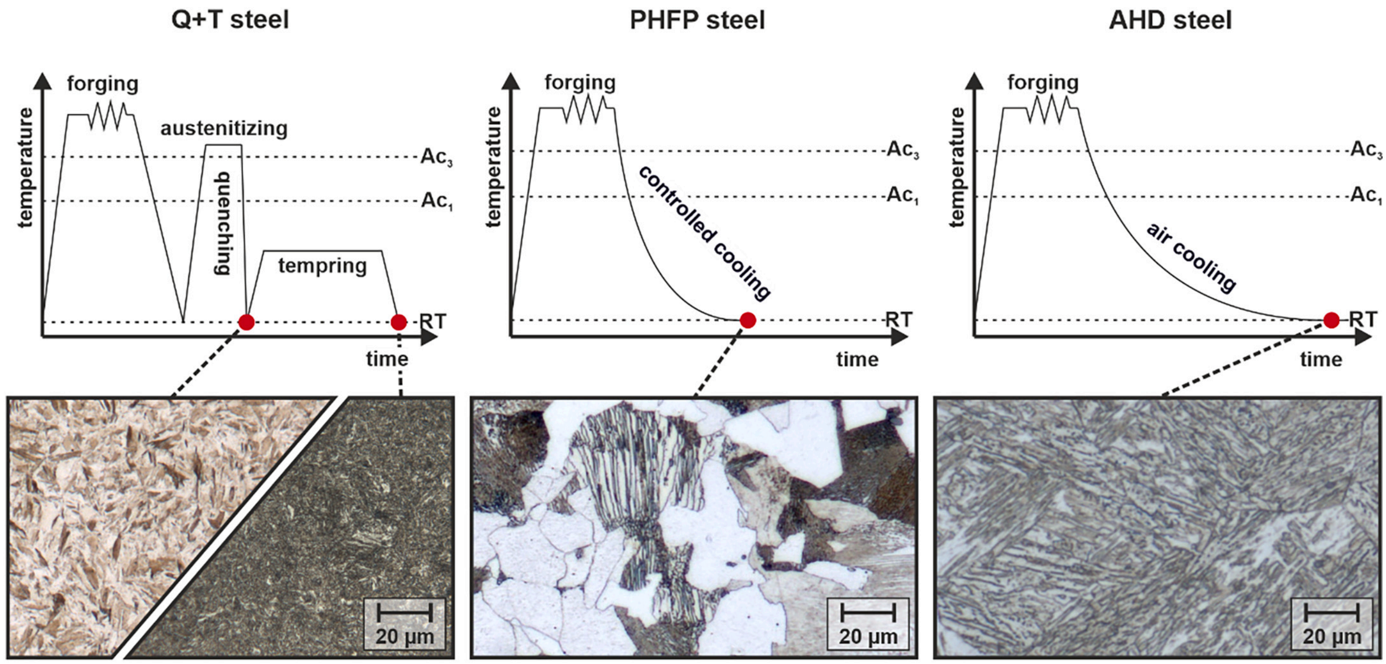

Fig. 1. Forging processes and consecutive heat treatments of quench and tempering (Q + T), precipitation hardening ferritic pearlitic (PHFP) and air hardening ductile forging steels (AHD) with their resulting microstructure (Figure by Authors).

Table 1
Chemical composition of the newly developed AHD steels and the standard Q + T steels 33MnCrB5–2 and 42CrMo4. The chemical compositions were determined by spark spectral analysis; carbon and sulphur were determined by combustion analysis. All concentrations are given in wt.-%.

	C	Si	Mn	P	S	Al	Cr	Ni	Mo	Nb	B
AHD [19]	0.15	0.50	3.90	0.004	0.002	0.52	0.10	0.05	0.24	0.030	0.0025
33MnCrB5–2 [19]	0.32	0.29	1.42	0.018	0.022	0.03	0.47	0.03	0.01	–	0.0030
42CrMo4 [16]	0.42	0.30	0.85	0.009	0.010	0.01	1.17	0.18	0.23	–	–

to cyclic mechanical properties. As a result, an LCA must consider three different aspects to enable a comprehensive comparison of the alloys: the change in chemical composition, the shortened process route, and the potential for lightweight design.

2.2. Environmental impact assessment

The application of lightweight design can result in an increased material efficiency. Many rather simplistic mass-based indices exist that evaluate the implementation of material efficiency strategies [10,20]. It is questionable if and how they reflect environmental impacts. Thus, it is highly recommended to conduct proper environmental assessment [21]. For this reason, the methodology of LCA was chosen to analyze the U-bolt in terms of the change in chemical composition, production route, and application of lightweight design.

2.2.1. Methodology

The ISO 14040/14044 is the basis for the analysis conducted within this study [22,23]. The general approach of LCA consists of four steps: (1) definition of goal and scope, (2) inventory analysis, (3) impact assessment and (4) interpretation.

In section 2.2.2, the aim, the functional unit, and the system boundaries are described. The subsequent sections describe the analyzed product system in more detail, which forms the basis for the life cycle inventory (LCI). The derived LCI is attributed to three impact categories, CF, CED, and MF. The categories are chosen as the steel industry is carbon-, energy- and resource-intensive [2,8,31]. The chosen indicators cover these environmental dimensions that are relevant to the case study.

The CF is defined in CO_2 equivalents and the characterization factors for global warming potential 100a are given by the IPCC 2007 report. The CED quantifies the energy content within all energy sources required in the product system. It is investigated by applying the equally named energy accounting method. The MF measures the abiotic and biotic material taken from nature as an input to the product system including unused extraction. The indicator is calculated according to the concept of material input per service unit (MIPS) [24]. The characterization of elementary flows in the database is implemented and applied according to literature [24–27]. As Teubler et al. [28] already pointed out, the MF is more influenced by ores than e. g. the CF and CED. Therefore, the MF is expected to reflect the changes in alloy composition due to the relation to mining of ores. It also indicates the change in resource use and allows conclusions, if an increase of material efficiency can be achieved.

The calculations are carried out using the OpenLCA software and the database ecoinvent 3.6 with attributional cut-off approach [30,31].

2.2.2. Goal and scope

The aim of the analysis is to investigate the influence of the change in alloy composition on the environmental impact of one U-bolt. The question of whether changing the alloy leads to a better environmental performance refers to a unit of steel in the field of material development. But the change of alloy has effects on different levels. For example, it results in changed production processes and changed material properties that enable the implementation of lightweight principles. The change in alloy leads to the adaption of the production route as the heat treatment becomes redundant as described in Section 2.1. The beforementioned higher cyclic strength of the AHD steels indicates an increased service life of the U-bolt. It is of no use at it is longer than the lifetime of the truck in which it is installed. The change in mechanical properties allows an altered product design with a reduced material input, which is tested as well. From the perspective of life cycle thinking, the change in alloy composition and its consequences for the process and product design can impact the use phase and EoL. The use phase is excluded in the analysis as the U-Bolt is installed in a truck, and its weight proportion is between 0.005 and 0.05 wt.-%. The change in alloy composition can also lead to changes in the treatment of the material at the EoL. The recyclability is excluded as it is not part of the research project. Theoretical implications for the recyclability are discussed in Section 4.

In conclusion, the conducted environmental analysis of one U-bolt (2 kg) is limited to cradle-to-gate, which is visualized in Fig. 2 and described in the following sections. Generally, all inputs such as ores, auxiliary material, and electricity are modelled in the background system including the upstream processes.

Excluded from the system boundaries are transportation, packaging and finishing processes. The finishing treatments include shot blasting, cleaning and coating, which are considered unchanged for both processing routes. The production yield within the final quality control is excluded. There are some indications that the production yield might increase. But the data collected from the production on laboratory and industrial scale are not robust. Losses in steel production are considered. The impacts and benefits of recycling are allocated according to the recycled content approach [11,32]. The allocations are mass based, if not claimed differently.

2.2.3. Material composition

When it comes to the development of a new steel, the difference is found in the change of chemical composition. Environmental assessments mostly exclude the differentiation of a metal in terms of its exact chemical composition for simplicity reasons [35–37]. Few studies analyze the effect of varying alloying concept in relation to its environmental impact [33,42]. Rebec et al. [33] describe that basic data sets for raw and auxiliary materials were taken from ecoinvent and altered. The exact procedure is not described. Eckelman et al. [42] consider the mass-based composition of alloys and weigh them with emission factors. The study also includes the influence of using ferroalloys. Ferroalloys are composed of multiple elements with varying composition. Thus, the multitude of elements define an alloy and required adjustment mutually influence each other.

Both approaches were applied to three alloys of the present case study: 42CrMo4, 33MnCrB5–2 and AHD steels. The material composition results from own measurements and verification from product data sheets listed in Table 1. The impact factors were taken from literature [40–42]. The environmental impact related to the mass-based composition per kg of metal was calculated separately using the ecoinvent database [31]. The proportional amount of alloy was considered for the primary material, which is added during the steel production process. The 42CrMo4 contains 2.8 wt.-%, 33MnCrB5–2 2.6 wt.-% and AHD 5.5 wt.-% of alloying elements. Further, it is assumed that no primary chrome, i.e. ferrochrome, is required due to the chrome content available in steel scrap [43].

Generally, the exact composition of primary material added to the smelt within secondary metallurgy to adjust the alloy is mostly unknown. The manufacturers involved in the project did not provide specific data because of competition restrictions. This applies to the amount, quality and exact composition of alloying materials. Few data regarding the composition of ferroalloys such as ferroniobium and ferroboron are gathered from suppliers, which provided materials for the smelting process at laboratory scale. These data are considered and tested. For example, the used ferroboron consists of <20 wt.-% boron and mostly of iron.

The main assumptions are made according to the given information by the producer within the research project. Accordingly, the steel production including the smelting and secondary metallurgy for all alloys takes place in a 50 t EAF in Germany with up to 95% scrap input. The scrap content is rather high and thus considered as a best case. Further, a scrap content of 90% (base) and 85% (conservative) is tested. To compare the primary data and data from ecoinvent, data for the steel production via the EAF route from literature were used [35,45–47]. The production yield of the steel production is considered 81.3% and is based on the provided datasets. The electricity mix is relevant for the environmental impact of steel products, which was already shown by other studies [28,29]. As the place of production is in Germany, the source for the electricity required for each product system is a country-specific electricity mix provided by ecoinvent. The same applies for the natural gas required for the heat treatment and other processes.

2.2.4. Production processes

The steel production is followed by several manufacturing processes to produce the U-bolt. It includes ingot casting, blooming, hot rolling, cutting, forging and heat treatment as shown in Fig. 2.

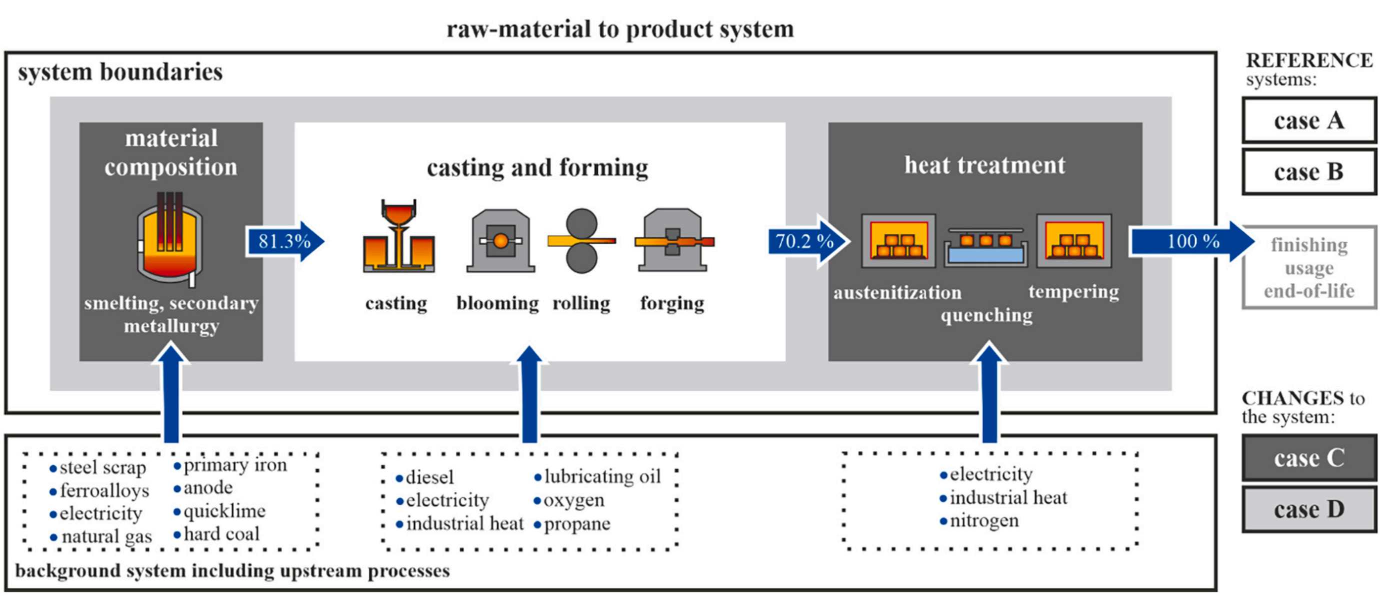

Fig. 2. System Boundaries of the analyzed Product System and its Variations (Figure by Authors).

Forming. The metal-shaping sector is difficult to grasp due to the diversity of processes and application. When it comes to bulk forming, only the study of Buis et al. [49] was identified. The authors stress the limited data provided by existing databases, its aggregation and offer an approach for quantifying energy consumption for hot forming processes such as billet heating, preforming and indirect extrusion. The results show that the billet heating dominates the hot forming processes. The factors affecting the energy consumption are (i) material forgeability, (ii) press/hammer design, (iii) furnace design, (iv) design of dies and lubricants and (v) part transfer. The inputs for the heating and deformation of the workpiece are a steel semi-product such as a billet, energy, e.g. electricity and natural gas, lubricants and die. Outputs are the formed workpiece, worn die, heat, expended lubricants and air emissions. The forging process in the production process of the U-bolt is classified as open die forging. The workpiece is heated with an induction coil. Then, the steel is compressed between two flat dies to decrease thickness and bend to the U-form. The workpiece is forged above its recrystallization temperature and thus, the process is termed hot forging. The developed AHD steels and the reference alloys were analyzed regarding their forgeability by hot compression tests. The flow curves of the materials show barely any difference in the investigated temperature range [19]. Therefore, it can be assumed that the material forgeability is comparable and there is no need to alter the forging process. As barely data were provided by the manufacturer regarding the forging process, the application of the UPLCI was not possible. Instead, the forging process from the ecoinvent database was used. The data set includes hot rolling, heating, forging and heat treatment. As the manufacturer within the research project provided primary data for the heat treatment, the process was substracted and separately defined. Losses occur during the various processes of forming, which result in a material efficiency of 70.2%, which is comparable to data from literature [35].

Heat treatment. The heat treatment consists of three phases, (i) austenitization, (ii) quenching and (iii) tempering and is energy intensive. Depending on the chosen medium, it is also related to high material input. Possible heat treatment equipment includes induction-coil heating, natural-gas fired furnace, electric resistance furnace in combination with oil, water, or salt bathes as quenching media. Reinhart et al. [50] suggests power measurements and the consideration of the energy consumption and time to evaluate manufacturing systems. This applies to the gathering of data for the heat treatment of the U-bolts. After forging, the products made from reference Q + T steels are austenitized, quenched and tempered. According to the manufacturer, the austenitization takes place in a gas-fired furnace followed by quenching. The tempering takes place in an electric furnace. The energy consumption and required natural gas are given for a certain period as well as the output of products. That allows a mass-based allocation. The same applies to the nitrogen used within the furnace, which passes into the ecosphere.

Compared to the 42CrMo4 and 33MnCrB5–2, the AHD steels does not require any additional heat treatment to gain the desired material properties.

Production yield. Within the research project, the production of the U-bolt was tested on an industrial production plant. An increased production yield after the heat treatment was noticed. This insight was part of informal communication. It is possible that the production yield increased because of increased care as it was a test batch. To substantiate a change of the production yield due to the choice of alloy, it requires the observation of a certain production volume. Yet, it is not given and therefore excluded from the analysis.

2.2.5. Product design

Another aspect influenced by the choice of alloy is the product design. Santero & Hendry [34] stress the relation between the amount of material required for a product and its ability to provide a certain function, which shows the importance of addressing the identical functional unit. Material choices and their related properties in combination with product design can lead to excessive functionality, e. g. load-bearing capacities, and offer cut down potentials. Cut down can be achieved by lightweight design principles [50].

As already stated before, the mechanical properties of the developed AHD steels differ from the 42CrMo4 and 33MnCrB5–2. Material testing proved that the cyclic strength doubles. That allows a longer use phase when keeping the same product design. As the prolonged lifetime of the U-bolt is restricted by the lifetime of the truck, it is of no benefit and reaches excessive functionality. Instead, it is possible to reduce the thickness of the product. Another product application of the AHD steels proved the feasibility of a weight reduction of 22.5 wt.-% [51]. This applies also to the U-bolt. Theoretically, a weight reduction of 50 wt.-% is possible according to the increase of cyclic strength. As it was not tested the proven weight reduction of the other workpiece made from the AHD was considered as a realistic scenario (medium). To test the influence of product design according to lightweight principles, a weight reduction of 10 wt.-% and 30 wt.-% is included.

2.2.6. Scenarios

Four different scenarios are tested in these studies as summarized in Table 2:

Case A is the reference system as it describes the original production process and the common alloy made from 42CrMo4 for the target application. Within the project of alloy development, most of the tested components are made of 42CrMo4 in practice. The U-bolt can be made of the alloy as well. The scrap content varies between 80% (low), 90% (medium) and 95% (high).

Case B also considers the original production process. The production route is based on the alloy 33MnCrB5–2, the original alloy for the U-bolt. Also, the scrap content varies between 80% (low), 90% (medium) and 95% (high).

Case C considers the new material composition and production process. The developed alloy (AHD) is used considering a scrap content between 80% (low), 90% (medium) and 95% (high). The production process excludes the heat treatment process, which becomes redundant due to the choice of alloy.

Case D considers the new material composition, production process and product design. Building on case C, it includes a weight reduction of 10 wt.-% (low), 20 wt.-% (medium) and 30 wt.-% (high).

3. Results and discussion

3.1. Material composition

First, the environmental assessment of alloys – 42CrMo4, 33MnCrB5–2 and AHD, was performed using the chemical composition in combination with carbon and energy intensities of the elements resulting from Nuss und Eckelman [40]. The results are listed in Table 3. Comparing the results of the three alloys, the results show no significant difference regarding the CF. All alloys are related to an impact of around 1.5 kg CO_2 eq per kg steel. The CED shows a perceptible difference. The 42CrMo4 is related to 23.3 MJ-eq per kg, the 33MnCrB5–2 to 23.1 MJ-eq per kg and the AHD to 23.8 MJ-eq per kg. Thus, the energy demand of the new developed AHD steels is perceptibly higher.

The results of the environmental analysis differ. The comparison of the alloys showed that especially the MF is highly sensitive to the input of ferromolybdenum. The 42CrMo4 and AHD steels contain the same percentage by weight of molybdenum. Due to the assumption that the added primary material composes of alloying elements only, the absolute input of molybdenum was significantly higher in the 42CrMo4. This does not reflect reality and led to an unreasonably high MF. To solve this distortion, the appropriate absolute amounts of alloys were calculated for the material input and are regarded as maximum values. Regarding

Table 2
Overview of the considered cases.

	Case A (42CrMo4)		Case B (33MnCrB5–2)		Case C (AHD)		Case D (AHD)	
	Scrap Content	Weight Reduction	Scrap Content	Weight Reduction	Scrap Content	Weight Reduction	Scrap Content	Weight Reduction
Low	80 %	0 %	80 %	0 %	80 %	0 %	80 %	10 %
Medium	90 %	0 %	90 %	0 %	90 %	0 %	90 %	20 %
High	95 %	0%	95 %	0 %	95 %	0 %	95 %	30 %

Table 3
Elementary based Carbon Footprint (CF) and Cumulative Energy Demand (CED) of the alloys 42CrMo4, 33MnCrB5–2 and AHD [40] and own calculations. C and Si were excluded as there was no data available in the cited reference.

	Mn	Cr	Mo	S	Al	Nb	B	N	Cu	Ni	V	Fe	Σ
CF in kg CO_2 eq/kg	1	2.4	5.7		8.2	12.5	1.5		28	6.5	33.1	1.5	
CED in MJ-eq/kg	23.7	40.2	117		131	172	27.3		53.7	111	516	23.1	
CF in kg CO_2eq/kg													
42CrMo4	0.0075	0.0264	0.012									1.5	1.5
33MnCrB5–2	0.014	0.0113	4E-4		2E-3		5E-5		8E-4	0.002	0.002	1.5	1.5
AHD	0.04		0.012		0.04	0.005	4.5E-5					1.4	1.5
CED in MJ-eq/kg													
42CrMo4	0.178	0.442	0.257									22.5	23.3
33MnCrB5–2	0.337	0.19	0.008		0.03		8.7E-4		0.016	0.033	0.026	22.5	23.1
AHD	0.948		0.246		0.67	0.064	8E-4					21.8	23.8

the varying scrap content, as soon as the alloy content was reached, the remaining primary material was primary steel. The CED, CF and MF are calculated for one kg of alloy including the smelting process. Further processing is excluded.

The results show that the AHD steels has a slightly higher impact in all three scenarios than the 42CrMo4 regarding the three covered impact categories. The difference is not significant regarding the CF, the CED, and the MF (<0.1 kg CO_2 eq, <1.7 MJ-eq, <0.7 kg). When comparing the AHD steels to the 33MnCrB5–2, the difference is larger (<0.2 kg CO_2 eq, <2.9 MJ-eq, <7.2 kg). The CF and CED of the AHD steels are higher than the impact of the original alloy. The relative difference in both categories is in the same range. The MF is significantly lower for the 33MnCrB5–2. This is due to the lower molybdenum content as shown in Table 1. Once again, the high material intensity of the alloying element and the associated sensitivity become clear.

Comparing the results to other studies, the conclusion seems plausible: The world steel association [52] provides global average data including sustainability indicators. In the year 2019, one kg crude steel had an average impact of 1.83 kg CO_2 eq. The energy intensity is 19.84 MJ/kg crude steel. The results of the world steel association are higher than the results of this study. It includes the global share of EAF, basic oxygen furnace (BOF) and open-hearth furnace. The EAF route is commonly referred to as "secondary route" and the BOF as "primary route". The energy and material consumption as well as the emissions of the BOF are by multiple factors higher than the EAF [53]. The share of EAF in the global average intensities of the worldsteel is 37% only [52]. The calculations in this study refer to solely EAF production. Another relevant factor is the energy mix. The German energy mix has a higher share of renewable energy and thus is less carbon intensive than the global energy mix, which further reduces the CF and CED [28,54].

Also, the results show the influence of varying scrap content. In both cases, all three impact categories increase while lowering the recycling content. This can be also explained in theory by the recycling approach chosen, as the scrap input has no embodied impact [11,32].

The comparison of the elementary-based calculation shown in Table 3 and the environmental analysis shown in Table 4 indicate the same tendency: The AHD steels has a higher environmental impact than the 42CrMo4 and 33MnCrB5–2. Though, the difference is higher when comparing the AHD steels with the 33MnCrB5–2. Even though, the AHD steels contains 5.5% and the 42CrMo4 contains only 2.8% of alloying elements. The comparison of the absolute impacts of both approaches is not possible. The elementary-based calculations include data calculated by Nuss und Eckelman [40] and the results of the environmental analysis base on the ecoinvent database [31], which have different scopes. The elementary-based calculation includes the impacts of the production of the individual metals. It covers the ore mining, concentrating, smelting, separating, and refining. It excludes the process for crude steel production itself. Further, it considers the material input to be primary material only. In opposite, the environmental analysis includes the smelting process of steel and assumptions regarding the scrap content.

According to Nicholson et al. [11] "Materials dictate a product's environmental profile". The context is EoL allocation methods, but it applies also to the influence of the choice of alloy [29,33]. The choice of a metal and its alloys depends on the target function, i. e. the product, with its mass, alloy composition, geometry and others [34]. Environmental assessments mostly exclude the differentiation of a metal in its alloys for simplicity reasons [35–37]. The worldsteel association [38] offers worldwide LCI data for 16 steel products, which are updated frequently. This is rather a first approach when compared to the multitude of materials and applications. The results of this study show two feasible approaches to analyze the influence of the varying alloying concepts on material level. They give the opportunity to approximate adjustment of the chemical composition. This case showed that the energy and resource demand are influenced perceptible. The CF is barely

Table 4
Cumulative Energy Demand (CED), Carbon Footprint (CF) and Material Footprint (MF) of 1 kg steel produced with varying scrap content (own calculations).

		42CrMo4			33MnCrB5–2			AHD		
		High	Med	Low	High	Med	Low	High	Med	Low
Scrap Content	%	95	90	80	95	90	80	95	90	80
CED	MJ-eq/kg	11.7	12.9	15.3	10.3	11.5	13.9	13	14.4	16.8
CF	kg CO_2 eq/ kg	0.7	0.8	1.1	0.6	0.7	1	0.7	0.9	1.2
MF abiotic	kg/kg	9.9	10.7	12.2	3.4	4.2	5.8	10.2	11.4	13

affected by the slight change of chemical composition. It should be noticed that the content of alloying elements is moderate. It should be investigated, if the result is also valid for high-alloyed steels and carbon-intensive alloying elements. Whereas the changes in chemical composition have a minor effect on the environmental impact, the height of scrap content and choice of energy mix are above all significant. Both are essential and should be given special consideration in the data collection.

There is a need to evaluate the environmental impact on material level. The analysis showed that data availability regarding metallic alloy is not sufficient [39]. Also, the databases for LCA such as ecoinvent offer only a limited amount of steel types and alloying elements [31]. There are impact assessments for metallic alloys, which give an idea of the range of environmental impact, but this information is not available for all types of alloys [40]. When evaluating steels on material level, there is also a demand for information about the varying environmental impact of ferroalloys in relation to their quality [41]. In summary, there is a need for a broader data basis to appropriately evaluate the change of alloying concept on material level including the various parameters.

3.2. Production process

After analyzing the influence of material composition on the environmental impact of the crude steel production, further manufacturing processes were included. The functional unit is one U-bolt, considering the system boundaries from a cradle-to-gate perspective. As described in 2.2.4, the heat treatment of the original production process becomes unnecessary. To analyze its influence, case A, B and C are compared.

As already stated, the production of the AHD steels (case C, D) leads to a slight difference regarding the environmental impact (CF, CED, MF) compared to the 42CrMo4 and 33MnCrB5–2. Compared to the other alloys, the CF (Fig. 3) of the AHD steels increases by 2.8–3.6% (case A) and 12.8%–19.6% (case B), the CED (Fig. 4) by 9.8–11.6% (case A) and 20.6%–25.9% (case B) and the MF (Fig. 5) by 2.8–6.3% (case A) and 126%–204.2% (case B). This indicates that the developed AHD steels leads to a slight increase of environmental impact regarding the steel production compared to the 42CrMo4 and 33MnCrB5–2.

When considering the entire production of a U-bolt, the influence of the change in steel production is insignificant when comparing the AHD steels to the 42CrMo4 (change in CF <2%, in CED <5%, in MF <5%) and to the 33MnCrB5–2 (change in CF <7%, in CED <10%).

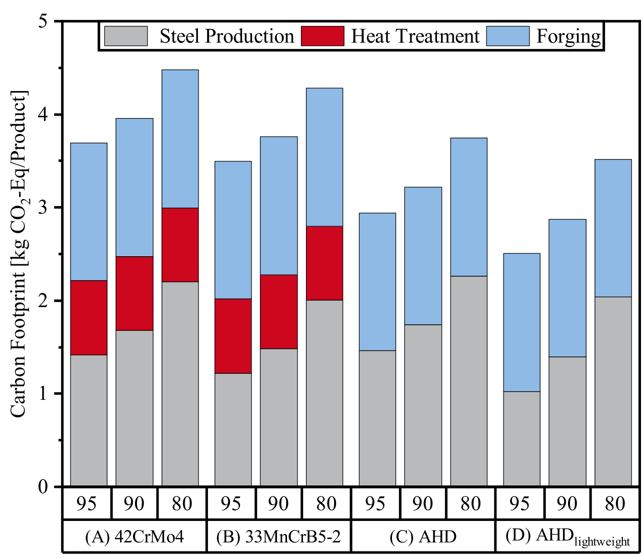

Fig. 3. Carbon Footprint of the production of one U-Bolt.
This figure contains the results for the Carbon Footprint in kg CO_2 eq for one U-bolt. The different scenarios consider a varying scrap content (high: 95%, medium: 90%, low: 80%), varying alloys: 42CrMo4 (A), 33MnCrB5–2 (B) and the AHD (C,D). The latter allows an altered production process (C) and product design (D).

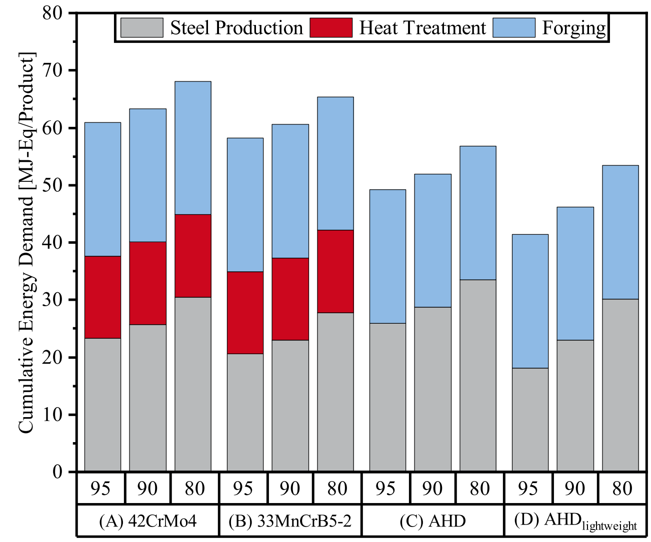

Fig. 4. Cumulative Energy Demand of the production of one U-Bolt.
The figure shows the CED in MJ-Eq for one U-bolt from a cradle-to-gate perspective. The different scenarios consider a varying scrap content (high: 95%, medium: 90%, low: 80%), varying alloys: 42CrMo4 (A), 33MnCrB5–2 (B) and the AHD (C,D). The latter allows an altered production process (C) and product design (D).

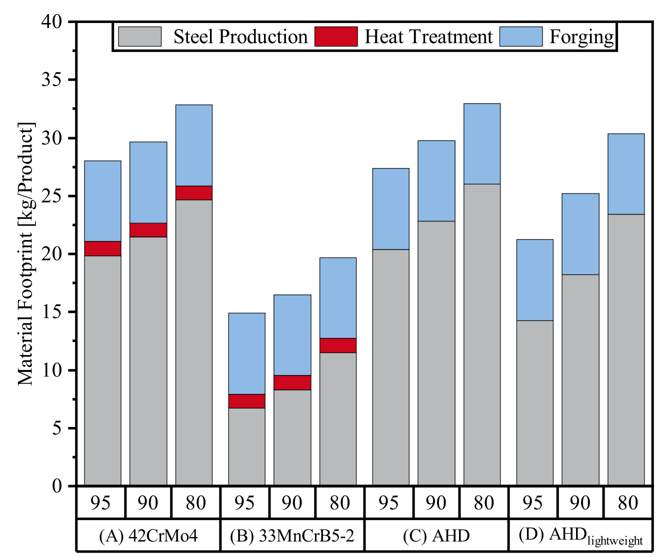

Fig. 5. Material Footprint of the production of one U-Bolt.
Here, the results for the MF in kg for one U-bolt are presented. The different scenarios consider a varying scrap content (high: 95%, medium: 90%, low: 80%), varying alloys: 42CrMo4 (A), 33MnCrB5–2 (B) and the AHD (C, D). The latter allows an altered production process (C) and product design (D).

Including the changed processing, the case C has a decreased environmental impact and CED compared to the original production routes (case A and B). The CF of case C decreases by 16.4%–20.3% compared to case A and by 12.5%–15.8% compared to case B. The CED of case C is between 16.7 and 19.3% lower compared to case A and between 13.2% and 15.5% lower compared to case B. The highest relative and absolute savings are achieved in the scenario with the highest recycling content.

The MF of case C is higher in most of the conventional production process cases. When comparing case A and C, the MF of case C is higher in the scenario with the highest recycling content. In contrast, the scenario with a medium and the lowest recycling content show a slightly lower MF for case B compared to case A. The influence of the redundant heat treatment leads to a decreased MF within case C. Only in the scenario with the highest recycling content, this decrease can compensate the increase of the higher MF related to the change in alloying elements. The change of the MF of a U-bolt lays between −2.4% and 0.5% and are insignificant. When comparing case B and C, the MF of case C is significantly higher due to the choice of alloy (67.4%–83.7%).

The results show that the induced change in production process leads to a decreased environmental impact. It significantly reduces the CED and the CF accordingly. In opposite, the decrease in MF due to the redundant heat treatment has a minor effect. The resource demand is dominated by the steel production and its primary material input.

The accompanying literature research showed that the metal-shaping sector is difficult to grasp. It is characterized due to the diversity of processes and application. Ingarao [14] stresses the general relation between the manufacturing processes and material choice as it influences the required material input. However, often aggregated data are published with inconsistent depth of production [14]. This leads to difficulties in terms of the search for appropriate comparative data. The review of Ingarao [14] shows the shortage of investigations of metal-shaping processes regarding environmental analysis. Also, a clear focus on energy is shown and other material inputs are often left out. It remains open, if auxiliary materials such as the worn die have a significant influence on environmental impacts. The approach of unit process LCIs (UPLCI) [48] is highlighted as it is applied multiple times in the metal-shaping context. The approach offers the advantage to systematically describe manufacturing processes and the relevant parameter. To properly fill gaps of data in case studies and for comparing and validating the results, conducting further UPLCIs are highly recommended. It conflicts with the confidentiality of industry data that is often required. Another opportunity is seen in a unique tool provided by a German association for forming, which allows the members from industry to easily calculate Product Carbon Footprints based on their internal processes. This tool offers the potential to anonymously collect data for relevant industry processes [59].

3.3. Product design

The comparison of the cases with the original product design, i.e. A, B and C, to case D, considering lightweight principles, show a reduction in environmental impact. Case D covers the decrease of product weight by 10 wt.-% (low), 20 wt.-% (medium) and 30 wt.-% (high) and considers a varying scrap content as well as the redundant heat treatment.

Comparing case A and D, the reduction of raw material input leads in all three scenarios to a reduction of environmental impact in all the categories covered. The CF decreases between 21.4 and 32.2%, the CED between 21.6 and 32.1% and the MF between 8.1 and 31.9%. The larger span of the MF reduction shows the higher sensitivity to metal ores of the indicator compared to the CF and the CED. In conclusion, the application of lightweight design leads to a reduction in every regard. This also applies to the ambivalent changes of the MF when comparing case A and C.

Applying the lightweight principles (case D) reduces the environmental impact compared to the U-bolt made of the 33MnCrB5–2 (case B). The CED is between 18.3% and 28.9% and the CF between 17.8% and 28.3% lower. The MF of the production route of the AHD (case D) is still between 42.6% and 54.2% higher than the original production route of the 33MnCrB5–2 (case B). Again, this huge difference to the comparison of case A and D is attributed to the high material intensity of molybdenum.

When comparing case C and D, all impact categories decrease. The CF decreases between 6.1 and 14.9%, the CED between 5.9 and 15.8% and the MF between 7.9 and 22.4%.

Generally, the developed alloy (AHD) is not environmentally beneficial focusing on the provision of steel compared to the original alloys 42CrMo4 and 33MnCrB5–2. When considering the redundant heat treatment, environmental benefits can be achieved. This only applies to the CF and CED. The MF is unambiguous compared to the 42CrMo4 and increases compared to the 33MnCrB5–2. When considering the changed mechanical properties and the related lightweight potentials, the environmental benefit of the alloy becomes clear.

The reduction of the MF implies also the increase in material efficiency according to lightweight design. The same service can be provided by a reduced mass of resources. Applying the lightweight design is in line with the circular economy, which is seen as a solution for combating climate change [3]. As initially stated, only a combination of material and energy efficiency measures is sufficient to meet the climate goals. The case study validates that an increased material efficiency can lead to an absolute reduction of resource and energy demand. At the same time, it reduces the carbon emissions and can be characterized as environmentally beneficial. Literature shows that lightweight design is only one of six strategies to increase material efficiency: (i) increase of product lifetime, (ii) intensifying product use, (iii) lightweight product design, (iv) reducing yield loss/ improving manufacturing processes, (v) other usage of fabrication scrap instead of melting, (vi) reuse strategies [9]. It is interesting that one aim of the initial research project related to the development of the AHD steels was to improve the cyclic strength and thus the product lifetime. That was successfully achieved and addresses a strategy of material efficiency as well. In the case of the U-Bolt, as long as it is no longer seen as a product but a component, which is installed in a truck, the increased product lifetime is of no use. It has excessive functionality as it has a longer lifetime than the truck. This case offered the opportunity to also apply the strategy of lightweight design and reduce the environmental impact. Still, it shows the value of changing the perspective to properly address and realize untapped potentials of the material efficiency strategies. This case study should also be investigated in terms of further strategies such as improving the production yield, which is so far only a presumption and requires further data collection on industrial level.

3.4. Data quality and limitations

The case study focuses on the importance to consider the material composition in a metallurgical development process. It stresses at the same time the importance of the resulting changes within the production process and product service. Including questions of environmental sustainability in the process of material development is important and so is life cycle thinking.

When it comes to the calculations, there were some difficulties. Regarding the alloy-specific assessment of material, the calculation using carbon and energy intensities from literature in combination with the weight-based composition of alloys is considered as a simplified procedure. It excludes the smelting process itself regarding various material and energy inputs, losses and does not account for secondary material. Thus, the results give the opportunity to compare alloys based on pure primary material input. Then again, the LCA-based environmental assessment requires the adjustment of data sets in ecoinvent regarding material composition, which has its advantages and disadvantages. Using predefined processes leads to including more comprehensive data and background systems. The provided data reflect also a defined system representing a certain scope in terms of geographical region. These might not exactly reflect the analyzed product system but is the best data and solution available. Furthermore, changes of material composition in steel production are implemented from the input perspective as data are more accessible. The resulting changes in outputs regarding elementary flows remain unknown and would require measurements on the production site. Using the LCA-based approach includes more relevant influencing factors such as the production route, energy required, secondary steel, regional differences and displays a more complex model closer to reality.

When comparing the two approaches, they result in the same ranking of alloys: There is an insignificant difference between the environmental impacts of the 42CrMo4 and the AHD. The AHD steels has a slightly higher impact. When comparing the AHD to the 33MnCrB5–2, the former has a higher impact especially for the CED and the MF. Due to the different scopes and assumptions, the results are not comparable. Regarding the assumption for the steel production, the ratio between scrap content and primary material input as part of the secondary metallurgy and its influence on the environmental performance is of major interest. The scrap communicated by the manufacturer is considerably high as it is known that alloying elements are added to adjust the chemistry. Statistics from steel associations include the scrap content derived from a market perspective (global: 32%, Europe: 54%), which are seemingly low as they include primary and secondary production routes. The associations also claim a scrap input of up to 100% for the EAF [55,56]. To test the influence of the scrap content, three variations (95%, 90%, 85%) were tested. The assumptions and datasets from ecoinvent were compared to literature and found to be in line [28,35,45–47].

Regarding the production yield, the steel production is considered 81.3% and is based on the provided datasets. Other studies from literature state production yields of the steel production of 88.2% and 88% [35,45]. The referred publications do not include the secondary metallurgy and its influence. The assumed production yield is therefore rather conservative. Both approaches leave some influencing factors aside such as behavior of individual alloying elements as they dissolve or separate in the melting process. Another aspect which needs to be considered is the change in iron content when using ferroalloys. Considering the covered case, information about the exact composition of the ferroalloys used in this case study were available for only three of the metals. Also, output quantities and tolerances of materials regarding increasing scrap content and its qualities have an influence [57]. Another aspect is the quality of ferroalloys, which can be shown with the example of manganese as part of investigated alloys. In comparison to the conventional forging alloys, the developed AHD steels requires high-quality manganese. Low-quality manganese would contain too much carbon, which disrupts carbon content again. High-quality manganese is more expensive and might lead to changes in the production chain increasing its environmental impact [58].

For the LCA, such in-depth differences are barely covered in databases. Databases provide only a limited amount of processed alloying elements so far. But there is an increasing number of studies in literature focusing on alloying elements, which improves the data and information availability [13,40,41,58]. Literature indicates that there is a significant variance regarding the environmental impact of alloys. For example, ferromanganese has a CF of 1 kg CO_2 eq/ kg and ferrochrome of 1.9 kg CO_2 eq/ kg. These data are provided by Nuss & Eckelman [40] and represent a global average. In comparison, Haque & Norgate [41] published impacts of ferroalloys produced in Australia, resulting in a CF for ferromanganese of 3.6 kg CO_2 eq/ kg and ferrochrome of 7.2 kg CO_2 eq/ kg. More precise information about the source of alloys used in a products system and impact data are required as for now it is strongly limited.

Additionally, the choice of categories should be discussed. This environmental analysis covers the CF, CED and MF as the steel industry is known to be carbon-, energy- and resource intensive. However, there are further methods for the life cycle impact assessment such as ReCiPe, CML and ILCD including further categories [61].

In terms of the resource perspective, the MF is chosen as it is considered to have a good applicability and includes the unused extraction, which forms up to one third of all material flows [24]. However, the development and update of the database is not institutionally anchored and is a deficiency. Also, it is criticized for incomplete inventories, which is substantial when it comes to region-specific differences [27]. The analysis showed a high sensitivity of the MF to molybdenum as a by-product in the copper production. The MF is sensitive to metal ores which might be useful for questions regarding the alloy development, but it might be misleading as this case study shows. The suitability should be further investigated with regard to alloying element specific impacts as well as the data availability and quality.

This study is limited to three environmental categories. When it comes to raw materials and alloys, further dimensions are relevant such as the supply risk from a geological, technological, economic, social and geopolitical perspective. Environmental implications are not limited to ecosystems but include e. g. vulnerability to supply restriction including the substitutability of metals. When it comes to steel, the alloys form the bottleneck of supply [40]. Here, another important aspect is the dissipation of the alloying elements, which influences the dependence on primary material. The dissipative losses are related to the behavior of the alloying elements in the recycling process [13]. Indicators can give insights of the dissipation of different metals such as iron along the entire life cycle. But not all metals are covered, and the frameworks are still under development [6].

Regarding the implementation of the environmental analysis, there is the dilemma between choosing an aggregated process from the database and relying on primary data only. This applies also to the processing of steel such as the heat treatment and the forging process. Aggregated datasets might cover a wider range of inputs and especially outputs, but the scope and application might be inappropriate. Taking the forging process as an example, there is one process provided by the database, which represents the forging process of a larger workpiece than the one analyzed. There are some differences such as the requirements for handling the workpiece, which needs technical equipment for the large workpiece. In opposite, small workpieces are often handled manually. Further, the newly developed material allows a reduced material input, which might also influence the process parameters. This is especially relevant to metal-cutting processes, which are resource-intensive and have a significant environmental impact [61]. Primary data are more accurate but might be (partly) unavailable and thus not comprehensive as in this case. Another option is to calculate input and outputs on a theoretical basis [49]. This also leads to the discussion of appropriateness of the underlying process system.

The recycling process is another example for consequences of the change in material composition. Due to the chemical composition, the AHD steels is expected to be identified easier within X-ray inspection as it is alloyed with an untypically high concentration of manganese. This could influence the sorting efficiency and purity of scrap and result in an increased recyclability. This is desirable as the processing of pure scrap within steel production results in the reduction of necessary dilution and addition of alloying elements [13,57]. So far this is based on theoretical implications and not tested in practice. The effect is difficult to quantify and remains a topic to be explored in future studies. The same applies to other slight changes such as the increased aluminium content in the AHD steels, which could lead to problems within continuous casting. Also, the application of lightweight principles and cut down of material of the workpiece could lead to changes of the forging process, e. g. reduced energy demand for deformation and heating. It must be evaluated in practice, if such small changes in weight and geometry does require a change in machinery setting.

4. Summary & conclusions

The steel industry is of great importance, when it comes to the overall global demand, its cross-sectoral integration and the resulting environmental impact. It is crucial to find solutions to reduce the environmental pressure of this industry. Recycling and thus making use of scrap as a secondary resource is an established strategy of material efficiency and achieved already enormous savings. It requires the implementation of further material efficiency measures to sufficiently reduce the environmental impact and be on track of the climate goals.

The implementation is highly product-centric and starts on material level as it defines the required functionality. Within a research project, a new AHD steel was developed. It aims to replace a Q + T steel commonly used in the automotive sector. During the development process, the potential of implementing lightweight principles as material efficiency strategy became clear and questions regarding the environmental sustainability arose. The presented case study of a U-Bolt offers insights regarding the material development. It evaluates the changes on material, process, and product level and its influence on the environmental performance. The case study was analyzed using the methodology of LCA. The focus is on the CF, CED, and MF as the dimensions are the most relevant to the steel sector.

First, the change of chemical composition was analyzed on material level using two approaches. The first approach included the combination of carbon and energy intensities and mass-based composition. As a second approach, the CF, CED, and MF were calculated according to the methodology of LCA. Both approaches indicate the same results. The developed AHD steels and the standard reference 42CrMo4 are in the same range of environmental impact. Compared to the 33MnCrB5–2, the AHD has a higher impact especially regarding the MF. However, the comparison of the results of both approaches in terms of absolute impacts is limited due to different scopes and database.

Secondly, the environmental performance of the production of a U-Bolt from a cradle-to-gate perspective was analyzed. The changes in the manufacturing process of the AHD steels, meaning a redundant heat treatment, compared to the original process of 42CrMo4 and 33MnCrB5–2 were included. It leads to a reduction regarding the CF and CED. Though, the MF was ambiguous for 42CrMo4. Depending on the assumed recycling content, the decrease of the MF due to the changed production process was compensated by the higher MF of the AHD steels as an alloy. Regarding the comparison between the production route of the AHD steels and the 33MnCrB5–2, the MF of the original production process remained significantly lower. The influence of the changed composition on the environmental impact is insignificant when considering the impact of the entire production process.

Thirdly, the possible lightweight design of the AHD steels was considered. This is due to the superior material characteristics. The weight reduction of up to 30 wt.-%, leads to clear environmental benefits and increases significantly the material efficiency. Compared to the original production routes, this leads to savings up to around 30% for the CF, CED and MF. One exception is the MF, which is still considerably higher for the U-Bolt made from the AHD compared to 33MnCrB5–2.

The case study shows how the implementation of the principle of lightweight design can lead to an increased material efficiency. At the same time, it shows the reduced energy demand and environmental saving potential, which is required considering the climate crisis. From a methodological point of view, it stresses the importance of taking a holistic view on material development. Answering the question, if the AHD steels is more sustainable than the commonly used 42CrMo4 and 33MnCrB5–2 on a material level would have been misleading. Considering possible changes in the manufacturing process and the product application showed the changes in terms of the environmental performance more comprehensively. This only became clear by considering the functionality, the excessive cyclic strength and the potential for lightweight design. By implementing the strategy of material efficiency, the environmental benefits increase significantly.

When it comes to the environmental assessment, difficulties arise regarding the data availability for the quality of alloying elements as material inputs and detailed changes of metalworking processes. This is partly in conflict with the high sensitivity of such information and data in the steel industry, e. g. material input to adjust the alloy during smelting processes. Regarding the EoL of the product life cycle, some theoretical indications for changes exist but are so far barely quantifiable. Also, the case study shows the need and interest of the metalworking industry to consider the environmental perspective regarding changes in the production chain.

Funding

Results presented here are from the research project IGF 27 EWN. Funding was provided by the German Federal Ministry of Economics and Energy via the German Federation of Industrial Research Associations “Otto von Guericke” (AiF) in the programme to encourage the industrial Community research by a resolution of the German Bundestag and the Steel Forming Research Society (FSV). The long version of the final report can be ordered after the end of the project from the FSV, Goldene Pforte 1, 58093 Hagen.

The project Circle of Tools [033R230F] is funded by the German Ministry of Education and Research.

CRediT authorship contribution statement

Wiebke Hagedorn: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Alexander Gramlich:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Kathrin Greiff:** Writing – review & editing, Resources. **Ulrich Krupp:** Writing – review & editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The project-based employment of Alexander Gramlich and Wiebke Hagedorn is financed by public funds. Both projects are listed below. Alexander Gramlich worked for the research project IGF 27 EWN. Wiebke Hagedorn is involved in the project Circle of Tools, which was not directly included in the study.

Data availability

The data that has been used is confidential.

References

[1] OECD, Global Material Resources Outlook to 2060, OECD Publishing, Paris, 2019.
[2] H. Ritchie, M. Roser, Emissions by Sector. https://ourworldindata.org/emissions-by-sector, 2021 (accessed March 12, 2021).
[3] Edgar Hertwich, Reid Lifset, Stefan Pauliuk, Niko Heeren, Saleem Ali, Qingshi Tu, Fulvio Ardente, Peter Berrill, Tomer Fishman, Koichi Kanaoka, Joanna Kulczycka, Tamar Makov, Eric Masanet, Paul Wolfram, Resource efficiency and climate change: material efficiency strategies for a low-carbon future, Zenodo (2019), https://doi.org/10.5281/ZENODO.3542680.
[4] L.D.D. Harvey, Iron and steel recycling: review, conceptual model, irreducible mining requirements, and energy implications, Renew. Sust. Energ. Rev. 138 (2021), 110553, https://doi.org/10.1016/j.rser.2020.110553.
[5] K.E. Daehn, A. Cabrera Serrenho, J.M. Allwood, How will copper contamination constrain future global steel recycling? Environ. Sci. Technol. 51 (2017) 6599–6606, https://doi.org/10.1021/acs.est.7b00997.
[6] C. Helbig, A. Thorenz, A. Tuma, Quantitative assessment of dissipative losses of 18 metals, Resour. Conserv. Recycl. 153 (2020), 104537, https://doi.org/10.1016/j.resconrec.2019.104537.
[7] S. Pauliuk, Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations, Resour. Conserv. Recycl. 129 (2018) 81–92, https://doi.org/10.1016/j.resconrec.2017.10.019.
[8] OECD, Steel Market Developments. Q2 2018, OECD, Paris, France, 2018.
[9] J.M. Allwood, M.F. Ashby, T.G. Gutowski, E. Worrell, Material efficiency: a white paper, Resour. Conserv. Recycl. 55 (2011) 362–381, https://doi.org/10.1016/j.resconrec.2010.11.002.
[10] R.L. Milford, S. Pauliuk, J.M. Allwood, D.B. Müller, The roles of energy and material efficiency in meeting steel industry CO_2 targets, Environ. Sci. Technol. 47 (2013) 3455–3462, https://doi.org/10.1021/es3031424.
[11] A.L. Nicholson, E.A. Olivetti, J.R. Gregory, F.R. Field, R.E. Kirchain, End-of-life LCA allocation methods: Open loop recycling impacts on robustness of material selection decisions, in: 2009 IEEE Int. Symp. Sustain. Syst. Technol., IEEE, Tempe, AZ, USA, 2009, pp. 1–6, https://doi.org/10.1109/ISSST.2009.5156769.
[12] P. Nuss, E.M. Harper, N.T. Nassar, B.K. Reck, T.E. Graedel, Criticality of Iron and its principal alloying elements, Environ. Sci. Technol. 48 (2014) 4171–4177, https://doi.org/10.1021/es405044w.

[13] T.E. Graedel, B.K. Reck, A. Miatto, Alloy information helps prioritize material criticality lists, Nat. Commun. 13 (2022) 150, https://doi.org/10.1038/s41467-021-27829-w.
[14] G. Ingarao, Manufacturing strategies for efficiency in energy and resources use: the role of metal shaping processes, J. Clean. Prod. 142 (2017) 2872–2886, https://doi.org/10.1016/j.jclepro.2016.10.182.
[15] Destatis, Genesis-Online. Datenlizenz by-2-0, 2021.
[16] H.-W. Raedt, F. Wilke, C.-S. Ernst, Initiative massiver leichtbau - leichtbaupotentiale im automobil durch massivumformung, Automob. Z. ATZ. (2014) 58–64.
[17] A. Gramlich, T. Schmiedl, S. Schönborn, T. Melz, W. Bleck, Development of air-hardening martensitic forging steels, Mater. Sci. Eng. A 784 (2020), 139321, https://doi.org/10.1016/j.msea.2020.139321.
[18] A. Gramlich, C. van der Linde, M. Ackermann, W. Bleck, Effect of molybdenum, aluminium and boron on the phase transformation in 4 wt.–% manganese steels, Results Mater. 8 (2020), 100147, https://doi.org/10.1016/j.rinma.2020.100147.
[19] A. Gramlich, W. Bleck, Tempering and Intercritical annealing of air-hardening 4 wt % medium manganese steels, Steel Res. Int. (2021) 2100180, https://doi.org/10.1002/srin.202100180.
[20] B. Corona, L. Shen, D. Reike, J. Rosales Carreón, E. Worrell, Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics, Resour. Conserv. Recycl. 151 (2019), 104498, https://doi.org/10.1016/j.resconrec.2019.104498.
[21] S. Walker, N. Coleman, P. Hodgson, N. Collins, L. Brimacombe, Evaluating the environmental dimension of material efficiency strategies relating to the circular economy, Sustainability. 10 (2018) 666, https://doi.org/10.3390/su10030666.
[22] EN ISO, Environmental Management - Life Cycle Assessment - Principles and Framework, ISO 14040:2006 + Amd 1:2020, 2020.
[23] EN ISO, Environmental Management - Life Cycle Assessment - Requirements and Guidelines, ISO 14044:2006 + Amd 1:2017 + Amd 2:2020, 2020.
[24] C. Liedtke, K. Bienge, K. Wiesen, J. Teubler, K. Greiff, M. Lettenmeier, H. Rohn, Resource use in the production and consumption system—the MIPS approach, Resources. 3 (2014) 544–574, https://doi.org/10.3390/resources3030544.
[25] M. Saurat, M. Ritthoff, Calculating MIPS 2.0, Resources. 2 (2013) 581–607, https://doi.org/10.3390/resources2040581.
[26] K. Wiesen, M. Saurat, M. Lettenmeier, Calculating the material input per service unit using the ecoinvent database, Int. J. Perform. Eng. 10 (2014) 357–366.
[27] K. Wiesen, M. Wirges, From cumulated energy demand to cumulated raw material demand: the material footprint as a sum parameter in life cycle assessment, Energy Sustain. Soc. 7 (2017) 13, https://doi.org/10.1186/s13705-017-0115-2.
[28] J. Teubler, S. Weber, P. Suski, I. Peschke, C. Liedtke, Critical evaluation of the material characteristics and environmental potential of laser beam melting processes for the additive manufacturing of metallic components, J. Clean. Prod. 237 (2019), 117775, https://doi.org/10.1016/j.jclepro.2019.117775.
[29] G. Liu, D.B. Müller, Addressing sustainability in the aluminum industry: a critical review of life cycle assessments, J. Clean. Prod. 35 (2012) 108–117, https://doi.org/10.1016/j.jclepro.2012.05.030.
[30] A. Ciroth, ICT for environment in life cycle applications openLCA — a new open source software for life cycle assessment, Int. J. Life Cycle Assess. 12 (2007) 209–210, https://doi.org/10.1065/lca2007.06.337.
[31] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, Int. J. Life Cycle Assess. 21 (2016) 1218–1230, https://doi.org/10.1007/s11367-016-1087-8.
[32] K. Allacker, F. Mathieux, S. Manfredi, N. Pelletier, C. De Camillis, F. Ardente, R. Pant, Allocation solutions for secondary material production and end of life recovery: proposals for product policy initiatives, Resour. Conserv. Recycl. 88 (2014) 1–12, https://doi.org/10.1016/j.resconrec.2014.03.016.
[33] K.M. Rebec, B. Markoli, B. Leskovar, Life cycle assessment of metal alloys for structural applications, IOP Conf. Ser. Mater. Sci. Eng. 329 (2018), 012003, https://doi.org/10.1088/1757-899X/329/1/012003.
[34] N. Santero, J. Hendry, Harmonization of LCA methodologies for the metal and mining industry, Int. J. Life Cycle Assess. 21 (2016) 1543–1553, https://doi.org/10.1007/s11367-015-1022-4.
[35] J.M. Cullen, J.M. Allwood, M.D. Bambach, Mapping the global flow of steel: from steelmaking to end-use goods, Environ. Sci. Technol. 46 (2012) 13048–13055.
[36] S. Nakamura, Y. Kondo, K. Nakajima, H. Ohno, S. Pauliuk, Quantifying recycling and losses of Cr and Ni in steel throughout multiple life cycles using MaTrace-alloy, Environ. Sci. Technol. 51 (2017) 9469–9476, https://doi.org/10.1021/acs.est.7b01683.
[37] The Aluminium Association, The Environmental Footprint of Semi-Finished Aluminium Products in North America. A Life Cycle Assessment Report, The Aluminium Association, 2013. https://www.aluminum.org/sites/default/files/LCA_Report_Aluminum_Association_12_13.pdf (accessed January 29, 2021).
[38] Worldsteel, Life Cycle Inventory Study. 2019 data release, Worldsteel Association, Brüssel, Beijing, 2019.
[39] I. Dolganova, F. Bosch, V. Bach, M. Baitz, M. Finkbeiner, Life cycle assessment of ferro niobium, Int. J. Life Cycle Assess. 25 (2020) 611–619, https://doi.org/10.1007/s11367-019-01714-7.
[40] P. Nuss, M.J. Eckelman, Life cycle assessment of metals: a scientific synthesis, PLoS One 9 (2014), e101298, https://doi.org/10.1371/journal.pone.0101298.
[41] N. Haque, T. Norgate, Estimation of greenhouse gas emissions from ferroalloy production using life cycle assessment with particular reference to Australia, J. Clean. Prod. 39 (2013) 220–230, https://doi.org/10.1016/j.jclepro.2012.08.010.
[42] M.J. Eckelman, L. Ciacci, G. Kavlak, P. Nuss, B.K. Reck, T.E. Graedel, Life cycle carbon benefits of aerospace alloy recycling, J. Clean. Prod. 80 (2014) 38–45, https://doi.org/10.1016/j.jclepro.2014.05.039.
[43] D. Panasiuk, I. Daigo, T. Hoshino, H. Hayashi, E. Yamasue, D.H. Tran, B. Sprecher, F. Shi, V. Shatokha, International comparison of impurities mixing and accumulation in steel scrap, J. Ind. Ecol. (2022), https://doi.org/10.1111/jiec.13246 jiec.13246.
[44] A. Gramlich, T. Schmiedl, U. Krupp, S. Schönborn, J. Baumgartner, Lufthärtende duktile Schmiedestähle für zyklische Beanspruchung, in: MassivUMFORMUNG, 2021, pp. 68–73.
[45] G. Baracchini, L. Bianco, F. Cirilli, T. Echterhof, T. Griessacher, M. Marcos, D. Mirabile, T. Reichel, T. Rekersdrees, H. Sommerauer, European Commission, Directorate-General for Research and Innovation, Biochar for a Sustainable EAF Steel Production (GREENEAF2): Final Report. http://publications.europa.eu/publication/manifestation_identifier/PUB_KINA29517ENN, 2018 (accessed April 29, 2020).
[46] C. Gao, D. Wang, H. Dong, J. Cai, W. Zhu, T. Du, Optimization and evaluation of steel industry's water-use system, J. Clean. Prod. 19 (2011) 64–69, https://doi.org/10.1016/j.jclepro.2010.08.013.
[47] A. Raimondi, G. Girotti, G.A. Blengini, D. Fino, LCA of petroleum-based lubricants: state of art and inclusion of additives, Int. J. Life Cycle Assess. 17 (2012) 987–996, https://doi.org/10.1007/s11367-012-0437-4.
[48] K. Kellens, W. Dewulf, M. Overcash, M.Z. Hauschild, J.R. Duflou, Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO2PE! Initiative (cooperative effort on process emissions in manufacturing). Part 1: methodology description, Int. J. Life Cycle Assess. 17 (2012) 69–78, https://doi.org/10.1007/s11367-011-0340-4.
[49] J.J. Buis, J.W. Sutherland, F. Zhao, Unit process life cycle inventory models of hot forming processes, in: Vol. 2 Syst. Micro Nano Technol. Sustain. Manuf., American Society of Mechanical Engineers, Madison, Wisconsin, USA, 2013, https://doi.org/10.1115/MSEC2013-1054. V002T04A011.
[50] M.A. Carruth, J.M. Allwood, M.C. Moynihan, The technical potential for reducing metal requirements through lightweight product design, Resour. Conserv. Recycl. 57 (2011) 48–60, https://doi.org/10.1016/j.resconrec.2011.09.018.
[51] H.-W. Raedt, T. Wurm, A. Busse, massiverLeichtbau., Automobiler Leichtbau durch Massivumformung, in: Ideen Form Geben 33 ASK Umformtech. 28–29 März 2019 Eurogress Aachen Tagungsband, Verlagshaus Mainz GmbH, Aachen, 2019, pp. 121–132.
[52] Worldsteel, Sustainable Steel Indicators 2019 and the Steel Supply Chain, Worldsteel Assoc, 2019. https://www.worldsteel.org/media-centre/press-releases/2019/sustainable-steel-indicators-2019.html (accessed July 7, 2020).
[53] X. Li, W. Sun, L. Zhao, J. Cai, Material metabolism and environmental emissions of BF-BOF and EAF steel production routes, Miner. Process. Extr. Metall. Rev. 39 (2018) 50–58, https://doi.org/10.1080/08827508.2017.1324440.
[54] IEA, Data and Statistics. https://www.iea.org/data-and-statistics/data-browser?country=GERMANY&fuel=Energy%20supply&indicator=TESbySource, 2022 (accessed March 30, 2022).
[55] Worldsteel, Steel and Raw Materials. Factsheet. https://www.worldsteel.org/en/dam/jcr:16ad9bcd-dbf5-449f-b42c-b220952767bf/fact%2520sheet%2520raw%2520materials%25202021.pdf, 2021 (accessed March 21, 2021).
[56] W.V. Stahl, Fakten zur Stahlindustrie in Deutschland 2020, 2020. https://www.stahl-online.de/wp-content/uploads/WV-Stahl_Fakten-2020_rz_neu_Web1.pdf.
[57] S. Dworak, J. Fellner, Steel scrap generation in the EU-28 since 1946 – sources and composition, Resour. Conserv. Recycl. 173 (2021), 105692, https://doi.org/10.1016/j.resconrec.2021.105692.
[58] W. Wei, P.B. Samuelsson, A. Tilliander, R. Gyllenram, P.G. Jönsson, Energy consumption and greenhouse gas emissions during ferromolybdenum production, J. Sustain. Metall. 6 (2020) 103–112, https://doi.org/10.1007/s40831-019-00260-8.
[59] Industrieverband Massivumformung, Einzigartiges Tool zur Ermittlung des Product Carbon Footprints [Press Release], 2021, pp. 103–112, https://www.massivumformung.de/fileadmin/user_upload/6_Presse_und_Medien/Pressemeldungen/2021/21-07-27-IMU_PM_PCF-Tool-FRED.pdf.
[60] W. Bleck, E. Moeller, in: W. Bleck (Ed.), Handbuch Stahl. Auswahl, Verarbeitung, Anwendung, 2017, Hanser Verlag, München. vom Bleck, da stehen zumindest die Kosten drin, Handbuch Stahl. Carl Hanser, 2018. ISBN: 978-3-446-44961-9.
[61] N. Khanna, P. Shah, M. Sarikaya, F. Pusavex, Energy consumption and ecological analysis of sustainable and conventional cutting fluid strategies in machining 15–5 PHSS, Sustain. Mater.Technol. 32 (2022), https://doi.org/10.1016/j.susmat.2022.e00416.