Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2024, 18(1), 98–109
https://doi.org/10.12913/22998624/176824
ISSN 2299-8624, License CC-BY 4.0

Received: 2023.09.22
Accepted: 2023.12.12
Published: 2024.01.15

Additive and Subtractive Manufacturing of Inconel 718 Components – Estimation of Time, Costs and Carbon Dioxide Emission – Case Study

Wojciech Zębala[1], Anna Gaweł[1*]

[1] Department of Production Engineering, Faculty of Mechanical, Cracow University of Technology, ul. Warszawska 24, 31-155 Cracow, Poland

* Corresponding author's e-mail: anna.gawel@pk.edu.pl

ABSTRACT

The article presents the cost analysis of three techniques that can be used to produce a cylindrical part from Inconel 718 nickel alloy. First of them allows the part to be shaped by additive manufacturing (AM). In the second technique the shape is obtained by forging. Both techniques require the use of machining to give the final dimensional and shape accuracy of the manufactured part. The third technique is based solely on machining operations. Research has shown that the most expensive technique for high-volume production is SLM/LMF. Based on the case study, it can be concluded that after a year of production using the SLM/LMF, forging and machining methods, the carbon dioxide emission is the biggest in the additive manufacturing. Optimizing the Ra and F_c parameters causes differences in carbon dioxide emissions. The turning process including machining optimization due to F_c characterizes a higher ability to produce parts than optimization due to roughness parameter Ra.

Keywords: additive manufacturing, Inconel 718 nickel alloy, SLM, LMF, Carbon dioxide emission, year production, substrative manufacturing.

INTRODUCTION

Inconel 718 is a heat and corrosion resistant nickel alloy that is widely used at high temperatures and has the potential to be used in cryogenic applications. This type of precipitation hardening nickel-chromium alloy has good tensile, fatigue, creep and fracture toughness at temperatures up to 700°C. Inconel 718 alloy is produced both by solidification and plastic processing such as gas turbine blades, instrumentation parts, as well as parts for the power and process industries can be manufactured from nickel alloys. These parts can be machined both in their original state and after curing. Difficult-to-cut materials are associated with high machining costs due to two main challenges: short life of the cutting tools and difficulty in achieving the required surface finish [1, 2]. For difficult-to-cut materials [3, 4], tool wear becomes a key cost factor alongside volumetric efficiency [5]. The duration and cost of a machining operation depends on the manufacturing process used to produce the part [6]. In the traditional approach, the shape of the part and dimensional accuracy are obtained by machining from a semi-finished product, among others in the form of a bar [7]. However, it is increasingly common to use additive manufacturing (AM) or forging to produce parts. In such cases, machining is used in the next steps to obtain the required shapes and improve the surface [8].

In a competitive global environment, the lowest possible cost is as much requirement as maintaining quality when defining a manufacturing process or technique [9]. Analysis of link chain has been successfully used to assess the efficiency of the production process [10, 11]. Studies have shown that it allows to increase profitability [12] and cost efficiency [13], when used for repetitive manufacturing processes or projects where costs are projected in relation to basic units such as: production times and rates or physical attributes of the product [14]. Additive manufacturing of metallic materials is an innovative method, which is associated with a decrease in dimensional accuracy compared to other methods. It is estimated that the surface roughness of parts produced by this method is at least several hundred micrometers. This necessitates the use of additional finishing methods to improve the surface quality [15]. If the required dimensions, accuracy of reproducing the reference element and appropriate roughness are achieved, there is no need to use roughing or finishing. This necessity exists when certain technological conditions are not met. Unforeseeable defects in the part manufacturing process and high costs currently prevent the use of this method in industrial scale [16].

Performance analysis of customized processes is currently of limited interest to researchers [18]. This article partly fills this gap by providing an analysis model that explores three techniques that can be used to fabricate a cylindrical Inconel 718 part: Technique 1 – the initial shape of the part is created by AM (SLM) (process 1) and finishing the part by machining (process 2); Technique 2 – the shape of the part is obtained by forging (process 1) and finishing the part by machining (process 2); Technique 3 – both processes are made by machining. In this work the cost-effectiveness of the three techniques was compared using a model that was developed as a research contribution. The model allows for the analysis of five main categories of costs that are accumulated during manufacturing: workpiece preparation, heat treatment, cutting tools, machining operations, and material. The total costs of the product manufactured by each technique is discussed in this paper.

RESEARCH METHOD

This research method consists of three steps. First, presents the developed cost model, on the basis of which three techniques of parts production can be assessed: machining of a semi-finished product obtained by additive manufacturing, forging and rolling of bars. Next, presents the verification of the cost model based on the cost analysis of the example case study. Cutting data used for finish turning processes was achieved by the optimization strategy. An analysis of carbon dioxide emissions based on times and power during the turning process for individual production techniques was also carried out.

COSTS MODEL

The cost model was built to analyze the total costs of the production process for each technique. The costs were analyzed in the following five cost categories: (1) semi-product manufacturing (2) heat treatment, (3) tools for machining process, (4) machining operations, (5) material.

An equation-based cost model was developed to compare the cost-effectiveness of the following three manufacturing techniques (1):

$$S = P_m + H + T + C + M \tag{1}$$

where: S – sum of costs for a particular technology [EUR], P_m – cost of semi-product manufacturing for particular technology [EUR], H – cost of thermal treatment of Inconel 718 cylindrical part [EUR], T – cost of tools used for roughing and finishing [EUR], C – machining cost for roughing and finishing [EUR], M – material cost for a particular technique [EUR].

Cost of semi-product manufacturing Z was calculated from the formula (2).

$$P_m = t \cdot P \cdot E \tag{2}$$

where: t – time for one part manufacturing [h], P – device power [kW], E – electricity rate [EUR/kWh].

The formula below was used to calculate the cost of material M (3):

$$M = RM \cdot W \tag{3}$$

where: RM – unit cost of raw material [EUR/kg], W – weight of cylindrical part [kg].

Calculations regarding the costs of cutting tools T during roughing and finishing turning were made on the basis formula (4):

$$T = CT \cdot NT \tag{4}$$

where: CT – average cost of one tool [EUR], NT – number of tools needed to made of the one part.

The costs to be incurred during the cutting process for roughing and finishing turning have been developed based on the following dependence (5):

$$C = ((TR_i \cdot P) + (TF_i \cdot P)) \cdot E \tag{5}$$

where: TR_i – turning time for roughing turning [h], TF_i – turning time for finishing turning [h], P – device power [kW], E – electricity rate [EUR/kWh].

Considering the efficiency of the drive system e, device power P can be calculated according to the formula (6):

$$P = \frac{F_c \cdot v_c}{60\ 000} \quad [\mathrm{kW}] \tag{6}$$

CASE STUDY

The case study examined the effectiveness of three manufacturing techniques for part production, shown in Figure 1. The part consists of three cylindrical surfaces and has a thread at the end of the third section. Physical parameters such as weight and dimensions of samples produced by three different techniques are presented in Table 1. The dimensions of the samples depend on the manufacturing technology. Shaft machining involves the highest need for rough machining, because the final element is produced by only one cutting technology. In addition, forging and 3D printing technology is characterized by greater possibilities of adapting shapes, therefore roughing and finishing is less labor-intensive. The dimensions of both technologies differ slightly from those expected due to the greater possibility of adjusting the final dimensions as opposed to shaft machining. One reference sample was produced for each manufacturing technology in this study. All samples were annealed at 1065°C for one hour and aged at 760°C for 10 hours. Precipitation hardening of the In 718 superalloy involves supersaturation from 1065°C with a gas atmosphere (He, Ar) plus next aging in 760°C per 10 h. The chemical composition and mechanical properties are presented in Tables 2 and 3. All samples were made of Inconel 718 nickel alloy. Sample 1 was produced by Technique 1 (SLM/LMF) on the AM250 Renishaw Laser Metal Fusion machine with a powder granule diameter in the range of (20 - 50) µm. The process parameters are summarized in Table 4.

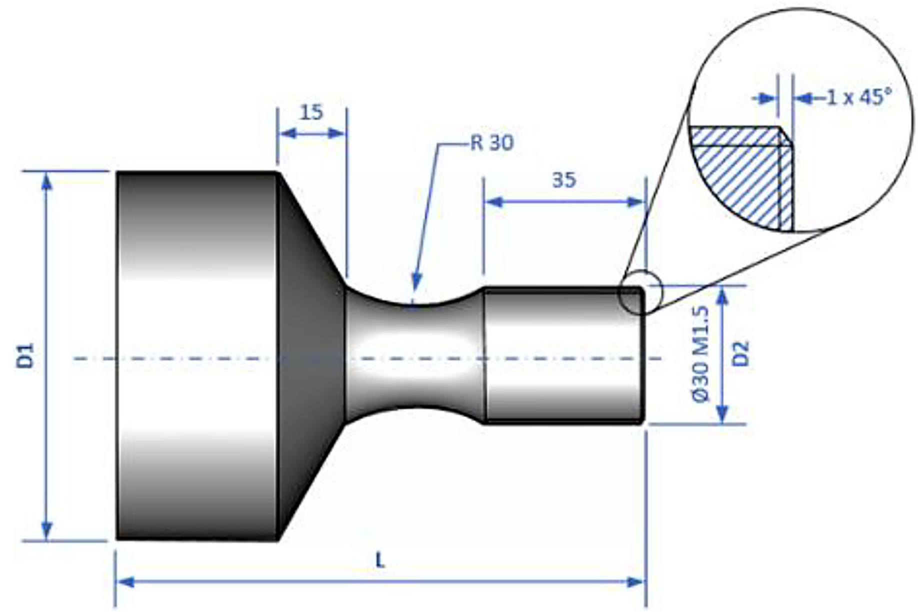

Figure 1. Sample of cylindrical part. Thread at the end (35 mm length)

Table 1. Specifications of samples

Sample type	Dimensions [mm]			Weight [kg]
	D_1	D_2	L	W
Sample 1 – SLM	80.4	31.4	115	2.143
Sample 2 – forging	82.4	33.4	115	2.271
Sample 3 – shaft	82.4	82.4	115	5.016
Finished part	79	30	115	2.027

Table 2. Chemical composition of Inconel 718 (wt. %)

Ni	Cr	Nb	Mo	Ti	Al	Co	Cu	C	Fe
50–55	17–21	4.75–5.5	2.8–3.3	0.65–1.15	0.2–0.8	<1	< 0.3	<0.08	residue

Table 3. Mechanical properties of Inconel 718 after heat treatment

Tensile strength (MPa)	Yield strength 0.2 % (MPa)	Elongation (%)	Hardness HRC
1230–1250	1020–1040	min. 12	48–49

Table 4. Process parameters of SLM

Process parameters	Value
Build rate	15 000 mm^3/h
Scanning speed	289 mm/s
Hatch spacing	65 µm
Laser power	185 W
Layer thickness	50 µm

Sample 2 was forged to a shape similar to the end part, while sample 3 was machined from rolled bar. Samples 1 and 2 required relatively little machining as opposed to samples 3 where the entire shape had to be made by a turning operation. Machining process was divided into roughing and finishing turning. Cutting data for roughing process are defined as follows: a_p = 1.5 mm, f = 0.115 mm/rev, and v_c = 200 m/min, where: a_p – depth of cut, f – feed and v_c – cutting speed.

Cutting data for finishing process was selected based on the optimization process according to the criteria: the lowest cutting force F_c and roughness parameter Ra (ISO 25178 and EUR 15178N). Ra is the most common parameter used during studying the cutting process [17] because of its stability [18]. Optimization was performed separately for the powder material and for the forging and the shaft. The experimental design plan was developed in accordance with the Taguchi method [19], which is a statistical approach to optimizing the parameters of the machining process and improving the quality of the manufactured elements. It is a simple, systematic and efficient methodology for optimizing process parameters. The method requires fewer tests than would be required for a full factor analysis, yet produces very similar results and achieves desired quality standards [20, 21]. The signal-to-noise (S/N) analysis strategy was adopted as "lowest is better".

A measuring system based on the Kistler 9257B force gauge and the Kistler 5070B amplifier by Kistler Company (Winterthur, Switzerland) was used. Surface roughness measurements and microscopic observations were carried out using a Taylor Hobson profilometer (Leicester, UK) and a Keyence 3D microscope (Osaka, Japan). A diamond-tipped stylus sweeps the surface and the results are processed by the software (Ultra). The surface was thoroughly cleaned by air pressure. Measurements are repeated at least three times to calculate average values. Table 5 and Table 6 show the cutting data selected for the research plan. These values are within the range recommended by the tool manufacturer for finishing with a CBN cutting tool. Longitudinal turning of shafts with a diameter of 50 mm was used in the tests. The test assumed a constant depth of cut a_p = 0,2 mm. According to the adopted test plan, the main cutting force F_c and surface roughness parameter Ra were measured, what is shown in Table 7 and 8, respectively. Rows marked in gray indicate cutting data that meets the optimization criteria (F_c and Ra) for the sample prepared by Technique 1 (SLM/LMF).

Figure 2 shows graphically the influence of the particular cutting data and cutting edge radius on the values of the main cutting force (Figure 2a) and surface roughness parameter (Figure 2b). The

Table 5. The variable values in the research plan, where r_e – nose radius

Trial	Coded parameter	Real parameter	Value			
			1	2	3	4
1	A	f (mm/rev)	0.077	0.115	0.153	0.173
2	B	v_c (m/min)	50	100	150	200
3	C	r_e (mm)	0.4			0.8

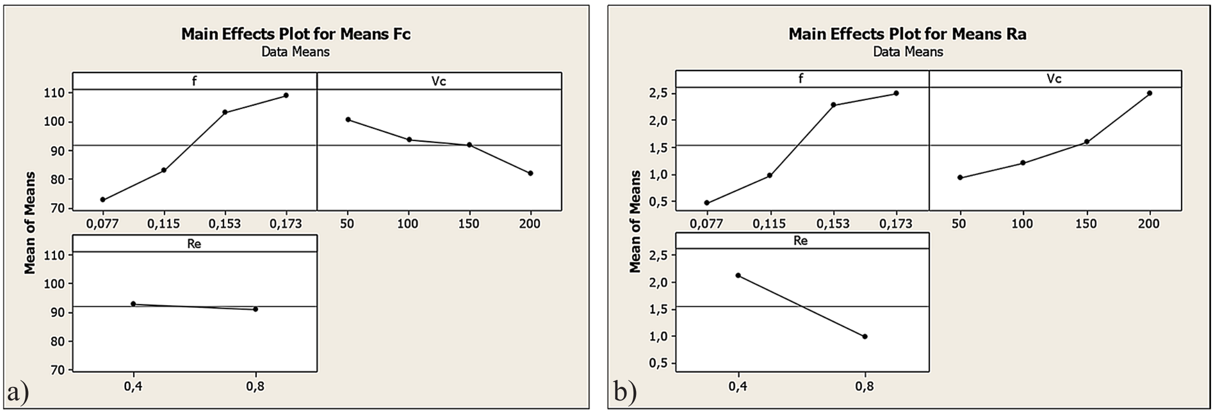

Figure 2. The influence of the cutting data and cutting edge radius on: a) Fc, b) Ra.

Table 6. Research plan with real values

Test	A	B	C	*f* (mm/rev)	v_c (m/min)	r_e (mm)
1	1	1	1	0.077	50	0.4
2	1	2	1	0.077	100	0.4
3	1	3	2	0.077	150	0.8
4	1	4	2	0.077	200	0.8
5	2	1	1	0.115	50	0.4
6	2	2	1	0.115	100	0.4
7	2	3	2	0.115	150	0.8
8	2	4	2	0.115	200	0.8
9	3	1	2	0.153	50	0.8
10	3	2	2	0.153	100	0.8
11	3	3	1	0.153	150	0.4
12	3	4	1	0.153	200	0.4
13	4	1	2	0.173	50	0.8
14	4	2	2	0.173	100	0.8
15	4	3	1	0.173	150	0.4
16	4	4	1	0.173	200	0.4

same optimization research was made for the samples prepared for Techniques 2 and 3 (forging and shaft). Results are shown in Table 9 and 10. Rows marked in gray indicate cutting data that meets the optimization criteria (F_c and Ra). Figure 3 shows graphically the influence of the particular cutting data and cutting edge radius on the values of the main cutting force (Figure 3a) and surface roughness parameter (Figure 3b). Table 11 presents the optimal cutting data according when the following two criteria are used for machining optimization: F_c – to minimize the main cutting force, and Ra to keep surface roughness parameter at the required level. The machining times for rough and finish machining of both parts are summarized in Table 12. Sample costs and rates required to produce one part are shown in Table 13._The material cost of each sample (Table 13) is determined based on the unit material cost required for each technique and the weight of each sample. Second, labor and waste rates are based on data collected from 10 companies producing industrial products. The sample size of the companies surveyed is considered sufficient as the data was needed to make an assessment, not to prove statistical validity. Machine rates are assessed based on list prices for CNC machines, software and experimental hardware. Overhead costs: coolant, energy are included in the price of the equipment. The average tool cost was calculated based on 2023 list prices from Haas Automation. The number of tools was derived from own tool wear laboratory experiments.

Table 7. The results of the optimization analysis for the cutting force F_c as the optimization criterion for the sample prepared by Technique 1 (SLM/LMF)

Trial	*f* (mm/rev)	v_c (m/min)	r_e (mm)	S/N	F_c (mean value) (N)
1	0.077	50	0.4	-38.14	80.66
2	0.077	100	0.4	-37.98	78.61
3	0.077	150	0.8	-36.77	68.75
4	0.077	200	0.8	-36.02	63.00
5	0.115	50	0.4	-39.03	89.18
6	0.115	100	0.4	-38.82	86.92
7	0.115	150	0.8	-37.97	78.93
8	0.115	200	0.8	-37.75	76.93
9	0.153	50	0.8	-41.08	113.03
10	0.153	100	0.8	-40.69	108.03
11	0.153	150	0.4	-40.30	102.23
12	0.153	200	0.4	-39.08	89.07
13	0.173	50	0.8	-41.55	119.43
14	0.173	100	0.8	-40.16	101.43
15	0.173	150	0.4	-41.41	116.73
16	0.173	200	0.4	-39.87	98.43

Table 8. The results of the optimization analysis for the Ra parameter as the optimization criterion for the sample prepared by Technique 1 (SLM/LMF)

Trial	*f* (mm/rev)	v_c (m/min)	r_e (mm)	S/N	Ra (mean value) (µm)
1	0.077	50	0.4	4.61	0.59
2	0.077	100	0.4	5.87	0.51
3	0.077	150	0.8	7.02	0.45
4	0.077	200	0.8	10.82	0.29
5	0.115	50	0.4	-0.93	1.11
6	0.115	100	0.4	0.66	0.93
7	0.115	150	0.8	-0.26	1.03
8	0.115	200	0.8	2.16	0.78
9	0.153	50	0.8	-0.10	1.01
10	0.153	100	0.8	-7.61	2.40
11	0.153	150	0.4	-5.74	1.93
12	0.153	200	0.4	-11.47	3.73
13	0.173	50	0.8	0.24	0.97
14	0.173	100	0.8	0.78	0.91
15	0.173	150	0.4	-9.30	2.92
16	0.173	200	0.4	-14.25	5.16

Samples produced by each technique have different costs. The unit cost of the raw material required for Sample 1 produced by Technique 1 is the highest. However, much less material is needed for Sample 1 than for Sample 3, where the entire shape must be machined off the roller. The maximum batch size (M_{max}) is determined by the capacity of the equipment required for part preparation (Samples 1 and 2) and heat treatment (Samples 1-3). Figure 4 presents a summary of costs for individual production stages, including: manufacturing, costs of material, heat treatment, cutting tool and turning processes. The values shown have been calculated for a single piece that can be made during a specific manufacturing process. The highest costs are noticeable for the cutting tools and then for the material. The heat treatment of Inconel 718 alloy is estimated at a similar level and amounts to about 15 EUR/piece. Additive manufacturing technology because of their high time of production has the highest costs. This is due to the longest production time for a single part and the increasing prices of electricity. It is also worth noting that this technology leads to anisotropy of the material. This parameter should be considered when selecting the appropriate technique, because such an element has different properties depending on the direction of measurement. There are also problems in adhesion between individual layers, which may contribute to a decrease in strength properties. While analyzing the highest production costs during turning it was observed for the machining process. This is mainly

Table 9. The results of the optimization analysis for the cutting force F_c as the optimization criterion for the sample prepared by Techniques 2 and 3

Trial	*f* (mm/rev)	v_c (m/min)	r_e (mm)	S/N	F_c (mean value) (N)
1	0.077	50	0.4	-38.4	83.4
2	0.077	100	0.4	-37.2	72.7
3	0.077	150	0.8	-36.2	64.3
4	0.077	200	0.8	-34.9	55.5
5	0.115	50	0.4	-41.6	119.7
6	0.115	100	0.4	-41.0	112.7
7	0.115	150	0.8	-39.7	97.0
8	0.115	200	0.8	-33.9	49.5
9	0.153	50	0.8	-43.0	141.0
10	0.153	100	0.8	-41.2	115.0
11	0.153	150	0.4	-40.3	103.0
12	0.153	200	0.4	-38.7	85.5
13	0.173	50	0.8	-43.9	156.8
14	0.173	100	0.8	-42.9	139.0
15	0.173	150	0.4	-40.1	101.0
16	0.173	200	0.4	-41.9	124.7

Table 10. The results of the optimization analysis for the Ra parameter as the optimization criterion for the sample prepared by Techniques 2 and 3

Trial	*f* (mm/rev)	v_c (m/min)	r_e (mm)	S/N	Ra (mean value) (μm)
1	0.077	50	0.4	0.02	1.00
2	0.077	100	0.4	-0.89	1.10
3	0.077	150	0.8	0.09	0.99
4	0.077	200	0.8	1.16	0.87
5	0.115	50	0.4	-3.25	1.45
6	0.115	100	0.4	-4.21	1.62
7	0.115	150	0.8	-2.10	1.27
8	0.115	200	0.8	-3.49	1.49
9	0.153	50	0.8	-3.34	1.47
10	0.153	100	0.8	-3.75	1.54
11	0.153	150	0.4	-7.02	2.24
12	0.153	200	0.4	-10.09	3.19
13	0.173	50	0.8	-6.85	2.20
14	0.173	100	0.8	-7.10	2.26
15	0.173	150	0.4	-12.62	4.27
16	0.173	200	0.4	-12.03	3.99

Table 11. Optimal cutting parameters when two criteria are used for finishing

Manufacturing technique	Machining optimization criterion	*f* (mm/rev)	v_c (m/min)	r_e (mm)
Technique 1 (SLM)	F_c	0.077	200	0.8
	Ra	0.077	200	0.8
Technique 2 and 3 (forged and shaft)	F_c	0.115	200	0.8
	Ra	0.077	200	0.8

Table 12. Roughing and finishing times (TR_i and TF_i respectively)

Type of sample	TR_i [s]	TF_i [s]	
		F_c	Ra
Sample 1 – SLM	78	100	100
Sample 2 – forging	107	75	100
Sample 3 – shaft	1328	75	100

Table 13. Costs and rates required for one part, where R_L – hourly labor time, R_{MT} – hourly equipment/machine tool rate, M_{max} – maximum number of parts that can be processed as a single load, *TPR* – thermal preparation, *WPR* – workpiece preparation

Costs and rates			Technique		
			1	2	3
Material cost	*RM* [EUR/kg]		45	22	18
	W [kg]		2.143	2.271	5.016
	SCR [%]		0.005	0.03	0.04
Average rates [EUR/h]	R_L		25		
	R_{MT}		50		
Tools [EUR]	*CT*		67		
	NT		1.3	2.3	4
Additive manufacturing	Maximum number of parts in batch	M_{max}	*WPR* [Euro/batch/series]		
		10	900		0
Forging	One series	10	0	1540	0
Forging matrix [EUR]	1500	One forging part*	4		
Heat treatment	Maximum number of parts in batch	M_{max}	*TPR* [Euro/batch]		
		10	225		

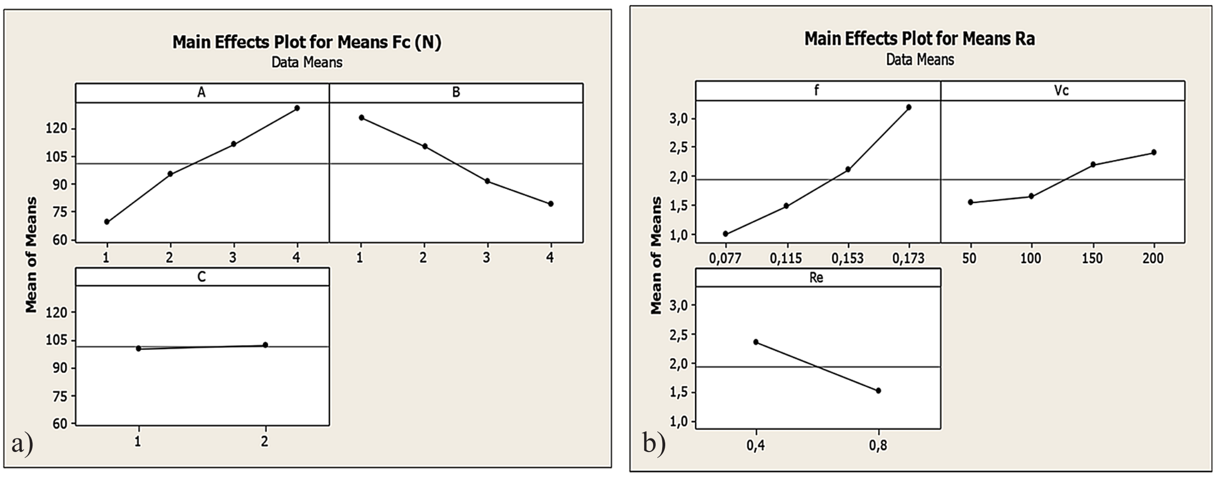

Figure 3. The influence of the cutting data and cutting edge radius on: a) F_c, b) Ra

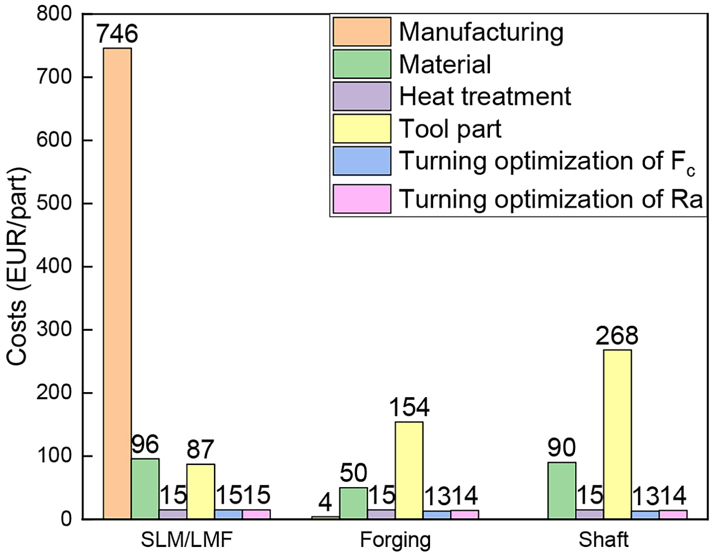

Figure 4. Comparison of costs for individual manufacturing techniques including machining optimization due to F_c and Ra

due to the longer process time, which is necessary to produce the final element, and the costs of cutting tools. The most cost-effective is the additive manufacturing technique, despite the highest material costs. Incremental techniques are characterized by anisotropy of properties, in which the material has different strength properties in different measurement directions. In this respect, forging surpasses this technology. The way the material is made during this process increases the strength of produced parts. Figure 5 presents a summary of the number of parts produced for three technologies of manufacturing a cylindrical part over the course of one year. The cost quantity model was calculated based on the times obtained from roughing and finishing operations. It was assumed that the calculations were made for a two-brigade company. Individual stops during work were also considered. The first was a break for the employee, which was 15 minutes for every 8 hours of work. It was assumed that statistically there are 21 working days in a month. Workplace would be shut down also during the transfer of the shift by employees, and the downtime would be another 15 minutes. In the Figure 5 it is possible to see the most noticeable differences after one year. Production using the

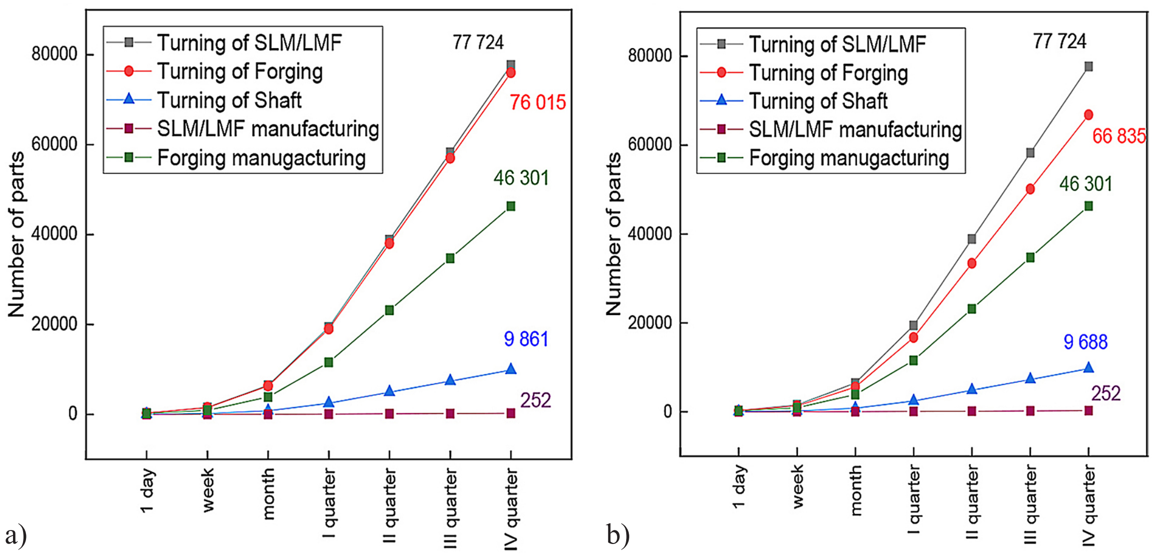

Figure 5. Number of pieces produced during the calendar year during turning and finishing process including machining optimization due to a) F_c and b) Ra

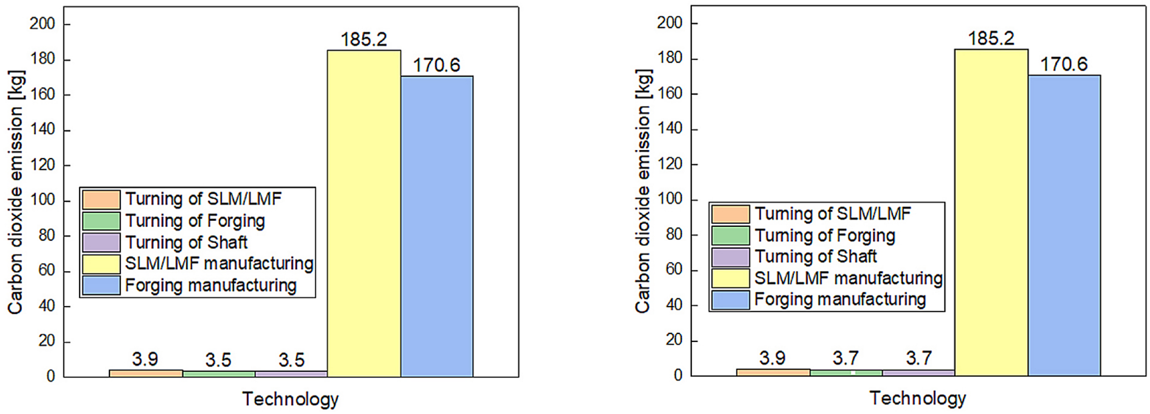

Figure 6. Carbon footprint for one produced cylindrical part by particular manufacturing process including machining optimization due to a) F_c and b) Ra

turning process, compared to additive manufacturing, is only 13% of the possibilities of the second technology. The number of parts produced using the machining method remains at a linear level, while SLM/LMF and the forging method increase significantly as a function of time. For each technique, there were excluded scraps. As it is possible to see the turning process including machining optimization due to F_c characterizes a higher ability to produce parts than Ra. SLM/LMF production is a small percentage of the removal of the cylindrical part. Therefore, in the graph above, the curve looks flat. If a different comparative scale were established, it would look completely different.

CARBON DIOXIDE EMISSION

In the article, calculations of carbon dioxide emissions were made for each of the individual manufacturing techniques. It was assumed that the value of 1 kW emits 657.1 g CO_2 into the atmosphere [22]. Based on the obtained results, an analysis of CO_2 emissivity to the atmosphere during the machining process was carried out. During the calculations, the dependence presented below (7) was used [23]:

$$E_{CO_2} = P \cdot h \cdot 0.6571 \tag{7}$$

where: E_{CO2} – carbon dioxide emission [kg], P – device power [kW], h – number of hours.

The work only estimates carbon dioxide emissions for additive manufacturing, shaft and forging. To analyze this problem in detail, the calculations carried out in this work should be enriched with carbon dioxide emissions during the production of the material intended for the element, type of production, and production efficiency. Figure 7 presents a summary of the Carbon footprint for one produced cylindrical part by particular manufacturing process. Carbon dioxide emission for samples produced by the SLM/LMF method remains at a similar level in relation to forging. It amounts to 185.2 kg and 170.6 kg of CO_2, respectively. In the case of the machining process, this value equals about 2% compared to CO_2 emissions for SLM/LMF technique. The highest carbon dioxide emissions occur for SLM/LMF production and amount to 201,735 kg after a year production. Optimizing the Ra and F_c parameters causes differences in carbon dioxide emissions. Forging and turning including machining optimization due to F_c criterion responds accordingly 174 823 and 22 678 kg of CO_2 per year. The second optimization, regarding forging and turning due to Ra criterion is accordingly 162 493 and 23 554 kg after one year production. The difference between each technique will result from the ability to produce the detail. At the same time, three different ways of producing the same part will generate different production quantities. As it was in case of energy usage the highest carbon dioxide emission is noticeable for additive manufacturing process [24, 25]. This is due the longest time needed to produce one part.

CONCLUSIONS

Total manufacturing cost was calculated as a function of equipment utilization rates, which are costs of the: particular technology, semi-product manufacturing for particular technology, thermal treatment of Inconel 718 cylindrical part, tools used for roughing and finishing, roughing and finishing and material for a particular technique. Machining costs are very low for Technique 1 (SLM) regardless of optimization criteria, especially when compared to material costs. Processing costs for Techniques 2 and 3 are slightly higher when Ra as opposed to Fc is used for optimization. The machining cost was found to be 25% of the material cost for Technique 2 and 15% for Technique 3.

Technique 2 based on forging is always the most cost-effective than the other two techniques. Technique 3 is as profitable as Technique 2 only when a single item needs to be produced. The unit cost of the raw material required for Sample 1 produced by Technique 1 is the highest. However, much less material is needed for Sample 1 than for Sample 3, where the entire shape must be machined off the roller. The number of parts produced using the machining method remains at a linear level, while SLM/LMF and the forging method increase significantly as a function of time. Therefore, the total cost should be assessed in comparison to the planned produced number of pieces or continuous production time.

The operation of turning shows an increase in the production capacity of details for the SLM/LMF technique and forging. After a year of production using the SLM/LMF, forging and machining methods was calculated. The carbon dioxide emission for the SLM/LMF method is the highest due to the high power consumption, which is directly related to the longest production time of the element. The highest carbon dioxide emissions occur for SLM/LMF production and amount to 201,735 kg after a year production. Optimizing the Ra and F_c parameters causes differences in carbon dioxide emissions. Forging and turning including machining optimization due to F_c criterion responds accordingly 174 823 and 22 678 kg of CO_2 per year. The second optimization, regarding forging and turning due to Ra criterion is accordingly 162 493 and 23 554 kg after one year production. It is shown that machining optimization of F_c and Ra causes smaller differences in the capabilities of manufactured parts. In this regard, it is more cost-effective and in terms of carbon dioxide production optimization due to F_c criterium.

Each of the three technologies used in the above publication is associated with different production costs and carbon dioxide emissions into the atmosphere. It is also worth considering that they are characterized by a different structure of the material, which directly affects the strength properties. This is caused by different granularity of the structure, which will be the subject of subsequent research. In the course of the final design of performance characteristics, the method of manufacturing the element should be taken into account in addition to costs and CO_2 emissions.The limitations during the conducted research and calculations of estimated carbon dioxide emissions concerned mainly the production technology. Additive techniques are characterized by anisotropy of properties, increased surface roughness and connections between layers, which may affect the strength properties. Production from a shaft requires the greatest amount of rough machining in order to produce the designed element.

REFERENCES

1. Mamalis A.G., Grabchenko A.I., Fedorovich V.A., and Kundrak J., Methodology of 3D simulation of processes in technology of diamond-composite materials. Int. J. Adv. Manuf. Technol., 2009, 43(11–12), doi: 10.1007/s00170-008-1802-0.
2. Zębala W. and Matras A., Optimization of Free-form surface machining. Production Process in Mechanical Engineering – Research Reports, TU Kosice. 2009, 65–72.
3. Özel T. and Karpat Y., Predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks, Int. J. Mach. Tools Manuf., 2005, 45(4–5), doi: 10.1016/j.ijmachtools.2004.09.007.
4. Thakur B., Ramamoorthy D.G., and Vijayaraghavan L., Machinability investigation of Inconel 718 in high-speed turning, Int. J. Adv. Manuf. Technol., 2009, 45(5–6), doi: 10.1007/s00170-009-1987-x.
5. Tansel I.N., et al., Selection of optimal cutting conditions by using GONNS, Int. J. Mach. Tools Manuf., 2006, 46(1), doi: 10.1016/j.ijmachtools.2005.04.012.
6. Varotsis A.B., 3D Printing vs. CNC machining. 3D Hubs, 2018.
7. Rojek I., Mikołajewski D., Kotlarz P., Macko M., and Kopowski J., Intelligent system supporting technological process planning for machining and 3D printing, Bull. Polish Acad. Sci. Tech. Sci., 2021, 69(2), doi: 10.24425/bpasts.2021.136722.
8. Miranda-Molina L., Quinayas-Ortiz A., and Peña-Rodríguez G., Design and simulation of a

mechanical system for the machining of parts and printing in 3D (x, y, z), Rev. UIS Ing., 2020,19(4), doi: 10.18273/revuin.v19n4-2020010.

9. Layer A., Ten Brinke E., Van Houten F., Kals H., and Haasis S., Recent and future trends in cost estimation, Int. J. Comput. Integr. Manuf., 2002, 15(6), doi: 10.1080/09511920210143372.
10. Eliashberg J., Elberse A., and Leenders M.A.A.M., The motion picture industry: Critical issues in practice, current research, and new research directions, Mark. Sci., 2006, 25(6), doi: 10.1287/mksc.1050.0177.
11. Aspara J. and Tikkanen H., Creating novel consumer value vs. capturing value: Strategic emphases and financial performance implications, J. Bus. Res., 2013, 66(5), 593–602, doi: 10.1016/j.jbusres.2012.04.004.
12. Castrogiovanni G.J. and Bruton G.D., Business turnaround processes following acquisitions: Reconsidering the role of retrenchment, J. Bus. Res., 2000, 48(1), doi: 10.1016/S0148-2963(98)00072-1.
13. Finney A., Value chain restructuring in the global film industry. In: The 4th Annual Conference on ‘Cultural Production in a Global Context: The Worldwide Film Industries, Grenoble Ecole de Management, Grenoble, France, June 2010.
14. Lange J., Bergs F., Weigert G., and Wolter K.J, Simulation of capacity and cost for the planning of future process chains, in International Journal of Production Research, 2012, 50(21), doi: 10.1080/00207543.2012.661889.
15. Sebbe N.P.V., Fernandes F., Sousa V.F.C., and Silva F.J.G., Hybrid Manufacturing Processes Used in the Production of Complex Parts: A Comprehensive Review, Metals, 2022, 12(11), doi: 10.3390/met12111874.
16. Bassoli E., Defanti S., Tognoli E., Vincenzi N., and Esposti L.D., Design for additive manufacturing and for machining in the automotive field, Appl. Sci., 2021, 11(16), doi: 10.3390/app11167559.
17. Quinsat Y., Sabourin L., and Lartigue C., Surface topography in ball end milling process: Description of a 3D surface roughness parameter, J. Mater. Process. Technol., 2008, 195(1–3), doi: 10.1016/j.jmatprotec.2007.04.129.
18. Dong W. P., Sullivan P. J., and Stout K.J., Comprehensive study of parameters for characterizing three-dimensional surface topography II: Statistical properties of parameter variation, Wear, 1993, 167(1), doi: 10.1016/0043-1648(93)90050-V.
19. Yang W.H. and Tarng Y.S, Design optimization of cutting parameters for turning operations based on the Taguchi method, J. Mater. Process. Technol., 1998, 84(1–3), doi: 10.1016/S0924-0136(98)00079-X.
20. Selvaraj D.P. and Chandramohan P., Optimization of surface roughness of AISI 304 austenitic stainless steel in dry turning operation using Taguchi design method, J. Eng. Sci. Technol., 2010, 5(3).
21. Athreya S. and Venkatesh Y.D., Application of taguchi method for optimization of process parameters in improving the surface roughness of lathe facing operation, Int. Ref. J. Eng. Sci., 2012,1(3).
22. Kostowski W. and Barzantny M, Efektywność energetyczna i środowiskowa wybranych metod wykorzystania wodoru, Energetyka, 2022, 445–450.
23. Cuixia Z., Conghu L., and Xi Z., Optimization control method for carbon footprint of machining process, Int. J. Adv. Manuf. Technol., 2017, 92(5–8), doi: 10.1007/s00170-017-0241-1.
24. Garzon-Hernandez S., Arias A., and Garcia-Gonzalez D., A continuum constitutive model for FDM 3D printed thermoplastics, Compos. Part B Eng., 2020, 201, doi: 10.1016/j.compositesb.2020.108373.
25. Priarone P.C., Campatelli G., Montevecchi F.,.Venturini G, and Settineri L., A modelling framework for comparing the environmental and economic performance of WAAM-based integrated manufacturing and machining. CIRP Ann., 2019, 68(1), doi: 10.1016/j.cirp.2019.04.005.