A COMPARATIVE STUDY OF ENERGY CONSUMPTION OF SELECTIVE LASER SINTERING AND TURN-MILL MACHINING

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Müge Kahya, *m.kahya@etu.edu.tr, TOBB University of Economics and Technology, Mechanical Engineering Depatment, Söğütözü Avenue 43, Ankara 06560, Turkey*

Gökberk Serin, *gserin@etu.edu.tr*, TOBB University of Economics and Technology, Mechanical Engineering Depatment, Söğütözü Avenue 43, Ankara 06560, Turkey

Hakkı Özgür Ünver, *hounver@etu.edu.tr, TOBB University of Economics and Technology, Mechanical Engineering Depatment, Söğütözü Avenue 43, Ankara 06560, Turkey*

Nuri Durlu, *ndurlu@etu.edu.tr*, TOBB University of Economics and Technology, Mechanical Engineering Depatment, Söğütözü Avenue 43, Ankara 06560, Turkey

Osman Eroğul, *erogul@etu.edu.tr, TOBB University of Economics and Technology, Biomedical Engineering Department, Söğütözü Avenue 43, Ankara 06560, Turkey*

Osman Demir,*odemir@gata.edu.tr, Medical Design and Manufacturing Center at Gülhane Military Medicine Academy, General Tevfik Sağlam Avenue, Ankara, Turkey*

Erbil Oğuz, *eoguz@gata.edu.tr, Medical Design and Manufacturing Center at Gülhane Military Medicine Academy, General Tevfik Sağlam Avenue, Ankara, Turkey*

ABSTRACT

Additive manufacturing is an emerging manufacturing technique with two main subcategories based on the material it uses; polymer and metal. Selective laser sintering is the most widely used additive manufacturing technique which binds metallic powders with the use of laser power, and builds complex parts by adding layer by layer. As additive manufacturing produces net shape or near net shape parts with almost zero material waste, it is considered to be a promising clean manufacturing technique. In this study, energy consumption evaluation and comparison of manufacturing of Ti-6Al-4V based metal parts manufactured with selective laser sintering and machining. As a machining method, turn-milling processes are used in order to test complex shapes.

Keywords: Selective Laser Sintering, Energy Consumption, Machining, Ti-6Al-4V

1. INTRODUCTION

Additive manufacturing (AM) has been increasing its popularity by increment of material variety and various geometrical abilities. New technology additive manufacturing machines have become widespread not only usage with the aim of prototyping, but also the production of last product. AM technologies directly produce the last product using a CAD file without the need of tooling [1,2].

Existing CNC machining technologies have been widely used in industrial fields. Both turning and milling abilities of CNC machines are adequate for quite few products or parts. However, certain geometrical constraints intercept the usage of traditional machining abilities. In such cases, AM becomes a senseful manufacturing choice. Furthermore it has been foreseen that the usage of AM technologies is going to be ahead beside traditional manufacturing methods for any geometry.

Nowadays, researchers are trying to determine the effectiveness and efficiency of AM technologies. Mechanical properties and several optimization studies can be shown as the most popular research objects. In literature, several studies exist about energy consumption of traditional machining methods. However studies about the energy model of AM have not been sufficiently developed.

Luo et al. (1999) have studied on solid freeform fabrication (SFF) process and performed case studies on stereolithography (SLA), selective laser sintering (SLS), and fused deposition modeling (FDM) [3]. In literature, this study has accepted as fundamental resource. Sreenivasan and Bourell (2009) have performed a study on sustainability analysis of SLS from an energy standpoint. Energy specification of SLS has carried out and appropriate process conditions are researched. The best energy saving condition for SLS is obtained at room temperature for Nylon-12 [4]. Mognol and Perry (2005) have studied on energy consumption of additive manufacturing in the aspect of environmental effects. In order to obtain suitable process parameters, three types of additive manufacturing processes (Thermojet (305), fused deposition modelling (FDM) 3000 (Stratasys) ancl EOSINT M2SO Xtended (EOS)) have been tested for energy reduction. The most important process parameters of the additive manufacturing processes have been defined as manufacturing time for all processes and volume of support for FDM [5].

Yadroitsev et al. (2010) have carried out a study on the effect of process parameters on single track sintering on selective laser melting (SLM). Process parameters are selected as scanning speed and laser power. Also, layer thickness is considered [6].

Kellens et al. (2011) have studied on SLS and SLM using the tools as time study, power study and consumables study. SLS and SLM have been explored for their environmental impact and contributors by using life cycle analysis (LCA). Furthermore, improvement potentials have been compared for these processes [7]. Baumer et al. (2010) have studied on the energy consumption of the two major additive manufacturing processes: selective laser melting and electron beam melting. Using a specified geometry, experiments have been performed and the results were compared both for this study and earlier studies [8].

Baumer et al. (2011) have compiled notable available additive manufacturing studies on energy consumption. The methods, machine types, materials and several process parameters have been considered. Specific energy consumption results of several additive manufacturing processes have been reported. Specific energy consumption calculation has been carried out due to the experimental results [9]. Baumer (2012) has studied on economic and environmental performance of additive manufacturing. Also, the ability of create complex parts of additive manufacturing has explored [10].

Gutowski et al. (2006) have developed an energy model that includes idle consumption and cutting performance of machine. Total power has been calculated using idle required power and the multiplication of machining constant (*k*) and the rate of material processing [11]. The mentioned model separates the required power items as processing power and the others. Thus, this model simplifies calculation for complex systems such as SLS.

In this study the energy consumption of selective laser sintering (SLS) and machining has been compared by using experimental and inferential methods. Also, a theoretical energy model of SLS has been constructed.

2. SELECTIVE LASER SINTERING (SLS)

SLS has a working mechanism based on binding the metal powders by sintering with a CO_2 laser beam [12]. Parts have been fabricated by laying the metal powder as layer-by-layer.

SLS is a sintering process and by this reason is appropriate for a wide range of powder materials [1,13]. Process schema of SLS is shown in Figure 1.

The energy consumption of SLS is affected from several process parameters. These parameters are specified as laser power, scan count, scan spacing, hatch length and scanning speed. Laser power is identified as the power of laser (watts) while it scans the area of each layer. Scan spacing is defined as the distance between two adjacent laser scan lines. Scanning speed represents the speed of laser spot between heating points. And, hatch length is the distance covered by laser light along X- or Y- direction in single run. Scan count is the number of times the laser beam transverses a scan vector per layer [14].

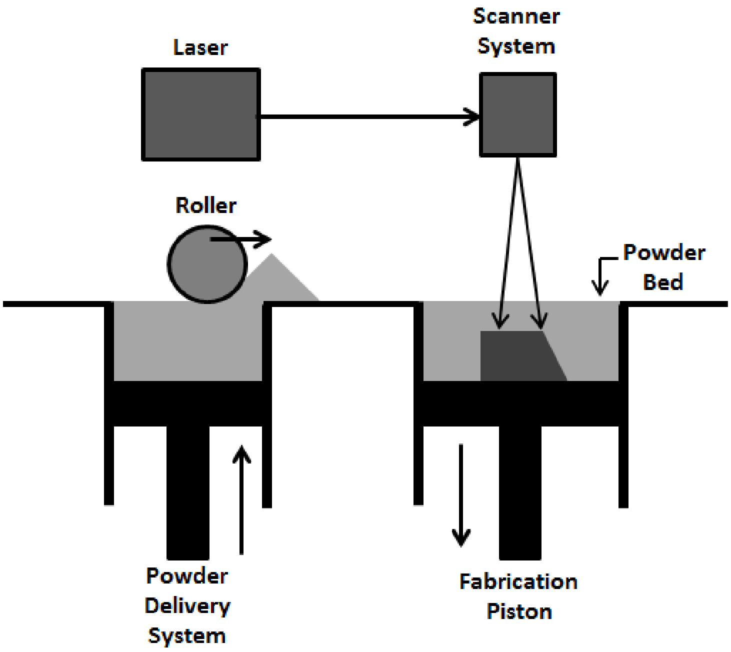

Figure 1. Process schema of selective laser sintering [15].

2.1. **Energy model of SLS**

As the energy consumption of selective laser sintering (SLS) is considered, the following approach could be followed based on the model that is developed by Gutowski et al. (2006).

$$P = P_0 + kQ \qquad (1)$$

In Formula 1, the model is shown; P is power demand, P_0 refers to idle power, k is a constant which specifies unit consumption per volume and Q is the rate of material processing. Using Formula 1, total energy consumption of process is calculated. In this study which is based on Gutowski's approach, E_{total} clarifies the total energy consumption of a SLS process. E_{total} is the sum of idle energy consumption ($E_{machine}$), the energy that is consumed while sintering ($E_{sintering}$).

$$E_{total} = E_{machine} + E_{sintering} \qquad (2)$$

$E_{machine}$ is the energy that is the measured total energy consumption except sintering operation. $P_{machine}$ is the unit power that is measured by average of a process. $\Delta t_{machine}$ is the total time in which the machine is working. Thus, $E_{machine}$ includes the energy of auxiliary parts. The value of consumed energy of auxiliary parts is the total energy that is consumed by the all other sections of the machine. The auxiliary systems that have indirect effect to process are specified as oxygen sensor mechanism that controls the oxygen ratio in the chamber, argon pump that feeds argon into the chamber, powder roller that provides continuity of metal powder feed to the table, powder delivery system that brings metal powder to the chamber, fabrication piston that controls the layering process and the system that provides movement of the laser.

$$E_{machine} = P_{machine} * \Delta t_{machine} \quad (3)$$

$E_{sintering}$ is the total energy amount that is measured while the machine is performing sintering operation. In other words, $E_{sintering}$ symbolizes the energy consumed by laser. $E_{sintering}$ includes both support sintering and work park sintering operation as average. $P_{sintering}$ is the required power load during the sintering process. As $P_{sintering}$ is calculated by specific enery per volume and material process rate, $E_{sintering}$ reduces to k multiplied by volume of the material sintered. $\Delta t_{sintering}$ is the total time in which sintering is perfomed.

$$E_{sintering} = P_{sintering} * \Delta t_{sintering} = (k\ Q)\ \Delta t_{sintering} \quad (4)$$

$$E_{sintering} = k * Vol = SEL * Vol \quad (5)$$

In equation 5, k denotes specific energy of the laser used for sintering (SLE) and Vol is the volume that is sintered. Baumer et al. (2011) has been compiled several values of specific energy consumption values for common AM processes [9]. In these studies, k has been calculated by the total consumption of the machine, not the consumption of laser energy, only.

3. CASE STUDY

In order to calculate the volume of each feature of a workpiece, an industry standard which defines geometrical definitions, ISO-STEP AP 224, is utilized.

In order to standardize design stage in industry and avoid technical problems that occur at design stage, a feature based procedure has been developed by International Standards Organization (ISO), which is known as STEP standards series. Standard for the Exchange of Product Model Data (STEP) AP224 is the one of the application protocols located in the ISO 10303, which includes identification information of mechanical parts for using processing features.

Manufacturing features are defined as shapes called feature, representing the volume to be removed from the material using machining processes, transition features and replicate features. In this study, sample part has been designed due to STEP AP224. Figure 2 shows some of the features that are defined in this standard.

Experiments of this study are carried out at TOBB-ETU and Gülhane Military Medicine Academy (GATA). SLS process has been carried out with Concept Laser M2 cusing machine located at Medical Design and Manufacturing Center(METUM) at GATA. The measurement of energy consumption of SLS process has been performed with Chauvin Arnoux C.A. 8435 energy meter. Turn-mill operation has been performed with Mazak integrex i200-ST turn-mill machine located at TOBB-ETU, Advanced Manufacturing Laboratory. The measurement of energy consumption of turn-mill machining operation has been carried out with Socomec DIRIS A4 smart meter. In this study, energy consumption calculations of both SLS and turn-mill machining have been carried out using STEP AP224 standard. Energy consumption of each feature has been calculated separately, and then the sum of these values has been specified as total energy consumption of the process.

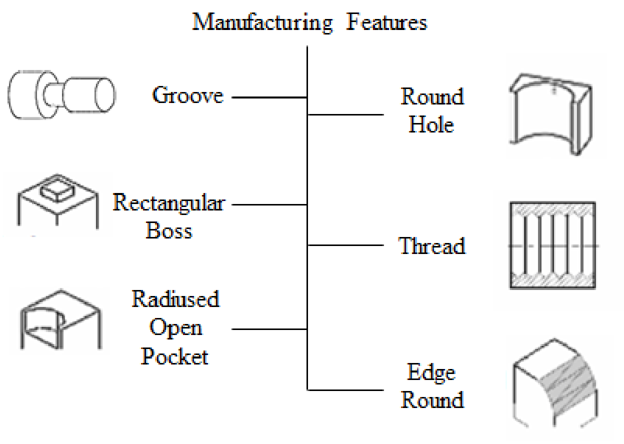

Figure 2. Manufacturing features used [16].

Feature based sample part is designed in order to specify different feature qualities. The sample part has outer diameter, tapered outer diameter, groove, radiused open pocket, edge round, rectangular boss, round hole and thread hole features.

Figure 3 shows the sample part. In Figure 4, the technical drawing of sample part is shown. It should be noticed that the sample part is a turn-mill part which involves both turning and milling operations.

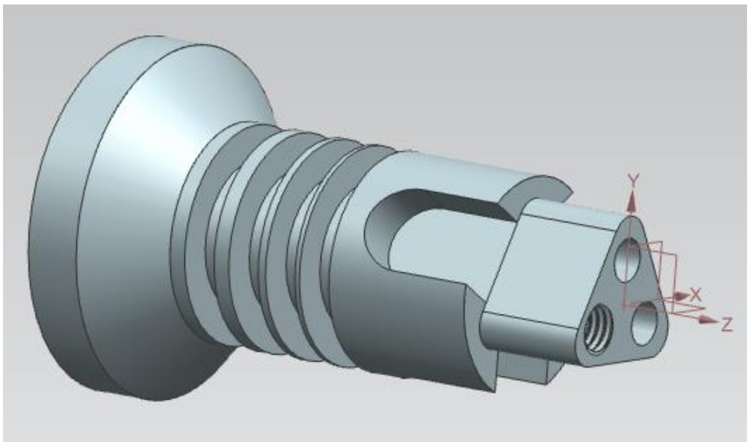

Figure 3. Sample part.

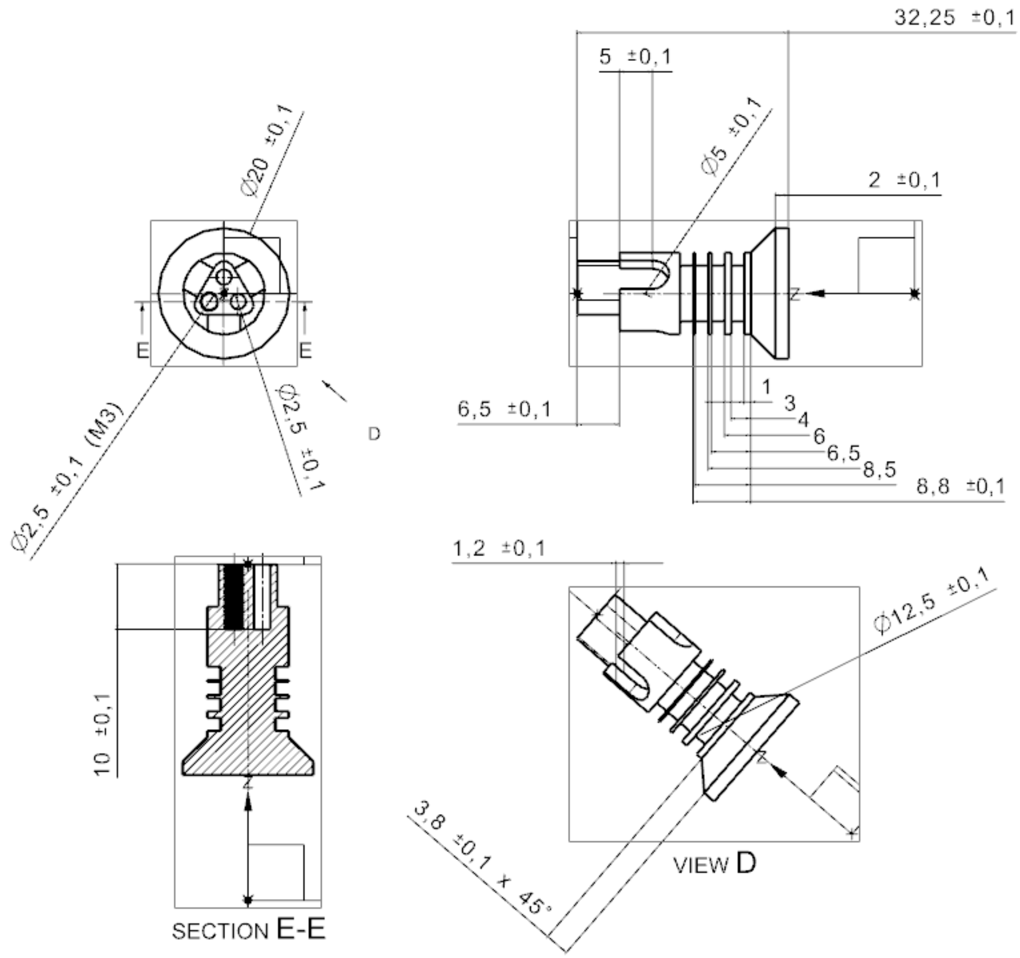

Figure 4. The technical drawing of sample part.

3.1. **Energy consumption of SLS for the material Ti-6Al-4V**

3.1.1. Prediction of consumed energy

The specified sample part has a volume of 3.0936 cm^3. The density of Ti-6Al-4V is 4.43 g/cm^3 [17]. Hence the mass of the sample part is calculated as 13.705 g. Specific laser energy value has been calculated due to the consumed energy by laser sintering operation during the processing of sample part. Measured energy consumption of laser has been divided by the mass of the sample part and then specific laser energy has been determined as 126 kWh/kg. In order to predict the total sintering energy consumption of Ti-6Al-4V for SLS process, the mass of the each feature is multiplied with 126.045 kWh/kg as it is listed in Table 1. Due to Formula 2, E_{total} has been calculated as the sum of $E_{machine}$ and $E_{sintering}$ as it is seen in Table 2. $E_{machine}$ has been calculated using the energy consumption data that is measured during processing of sample part. Due to the analysis of energy consumption of SLS machine, the energy that is not consumed by laser sintering operation, has been identified as $E_{machine}$.

3.1.2 Results of experiments

During the production of sample part by SLS process, consumed energy has been measured and energy consumption calculation has been carried out using the measured energy data. The consumed energy of production of the sample part is calculated as 38714.4 kJ.

Table 1. Energy consumption prediction of selective laser energy.

Features	Volume (mm^3)	Mass (g)	Specific Laser Energy (kWh/kg)	*Energy Consumption for Sintering (kJ)*
Outer Diameter	1430.4	6.337	126.045	*2876.4*
Groove	797.57	3.533	126.045	*1602*
Rectangular Boss	47.07	0.209	126.045	*93.6*
Radiused Open Pocket	818.64	3.627	126.045	1645.2
Total				*6217.2*

Table 2. Energy consumption prediction of selective laser sintering.

$E_{machine}$ (kJ)	$E_{sintering}$ (kJ)	E_{total} (kJ)
39247.2	6217.2	45464.4

3.2. **Traditional machining of Ti-6Al-4V**

3.2.1. Prediction of consumed energy

Energy consumption of turn-mill operation has been carried out due to the Formula 6 that is driven from Formula 1. Total energy consumption (E_{total}) has been calculated by the sum of $E_{machine}$ and $E_{cutting}$ due to Formula 1. $E_{machine}$ has been obtained by the energy consumption analysis of Moradnazhad (2015). In the study of Moradnazhad (2015), the energy characterization of Mazak Integrex I200-ST has been carried out [18]. The regressions developed in that study have been utilized in order to specify $E_{machine}$. $E_{cutting}$ is the energy consumption of cutting operation which is calculated using specific cutting energy.

$$E_{total} = E_{machine} + E_{cutting} \tag{6}$$

Specific cutting energy has been identified by Rajemi (2010) as 2.9 Ws/mm^3 for titanium alloys [19]. Kalpakjian and Schmid (2010) have indicated that specific cutting energy of titanium alloys should be in the range of 2-5 Ws/mm^3 [20]. Thus, specific cutting energy was obtained as 2.9 Ws/mm^3 in this calculation. Total predicted energy consumption for machining is estimated as 3303 kJ as give in Table 3.

3.2.2. Results of experiments

As the results of experimental stage, measured power requirement and calculated energy consumption values of different machining features are shown in Table 4. Under the process parameters column, parameters of each feature have been listed. 'Power required' column shows the average power load of each operation. Under the 'Auxiliary and constant power requirements' column, the average power loads of variable and constant components of machine load have been listed in related columns. The energy consumption of this operation was calculated as 3560 kJ.

Table 3. Energy consumption prediction of turn-mill machining.

Features	**Volume (mm^3)**	**k (Ws/mm^3)**	**Cutting Energy (kJ)**	**Machine Energy (kJ)**	**Total Energy (kJ)**
Outer Diameter	6125.12	2.90	*17.76*	*582.12*	*599.88*
Groove	527.79	2.90	*1.53*	*219.78*	*221.31*
Rectangular Boss	654.88	2.90	*1.90*	*1128.60*	*1130.50*
Radiused Open Pocket	87.04	2.90	*0.25*	*712.80*	*713.05*
Round Hole	147.26	2.90	*0.43*	*463.32*	*463.75*
Tread Hole	10.80	2.90	*0.03*	*17.82*	*17.85*
Total			***21.903***	***3124.440***	***3146.343***

Table 4. Energy consumption measurement of turn-mill machining.

	Process Parameters				***Auxiliary and constant power requirements***						
Features	Feed Rate (m/min)	Cutting Speed (m/min)	Milling Spindle Speed (rpm)	Turning Spindle Speed (rpm)	*Power Load (Watt)*	Feed Rate (W)	Milling Spindle Speed (W)	Main Spindle Speed (W)	Coolant Units (W)	Time (s)	*Energy (kJ)*
Outer Diameter	0.36	40		606	*6648.6*	10.38		396	3760	98	651.60
Groove	0.08	40		1019	*7403.3*	7.62		773	4680	37	273.60
Rectangular Boss	0.1	50	1326		*6593.7*	7.86	309		1920	190	1252.80
Radiused Open Pocket	0.35	57	3024		*6951.7*	10.29	243		3760	120	835.20
Round Hole	0.04	10	1273		*6773.5*	7.2	307		3760	78	529.20
Tread Hole	0.5	5	531		*6313.3*	11.78	265		1920	3	18.00
Total											***3560***

2.3. **Comparison of energy consumption of SLS and turn-mill machining**

The energy consumption value which is calculated using specific laser energy of SLS is 14 times higher than energy consumption value which is calculated using specific cutting energy of machining. The consumed energy value which is measured during the experiments of SLS is 10 times higher than consumed energy value which is measured during turn-mill operation. The comparison of SLS and machining energy predictions, plus their error values compared to measurements are given in Table 5.

Table 5. Comparison of experimental and calculated results

	Predicted Energy Consumption (kJ)	Measured Experimental Result (kJ)	Error (%)
Turn-mill Machining	3146.3	3560	11.6
SLS	45464.4	38714.4	17.4

4. CONCLUSION

An energy model of SLS has been proposed for energy consumption prediction based on Gutowski et al. (2006) [11]. Also, the comparison of SLS and machining energy consumption has been carried out in this study for Ti-6Al-4V. The results reveal that the energy consumption of SLS for the material Ti-6Al-4V is higher than the energy consumption of machined Ti-6Al-4V. The probable reason for this is the energy intensity of a SLS machine as opposed to the turn-mill machining center used. One of the reasons of the difference between these values is considered as the idle and auxiliary energy consumption difference in these two systems.

It is observed that required power of the SLS is actually 5 times lower than the required power of turn-mill machining. However, because of the process time of SLS is 70 times longer than the process time of turn-mill machining, energy consumption of SLS turns out to be much higher than turn-mill machining inherently.

In order to decrease the consumed energy per unit for SLS process, production rate per process should be increased. As geometric conditions are suitable, producing work parts in batches is essential to reduce energy consumption per part. Also, process cycle time should be decreased by increasing the layer thickness and laser scan speed, if this does not hurt part requirements such as surface roughness.

At this point, energy consumption of SLS can be only estimated roughly. Future work of this study has been planned as mode detailed energy measurement of the inner components of selective laser sintering process and profile individual energy demand of each of them.

Nomenclature

AM	Additive Manufacturing	LCA	Life Cycle Analysis
CAD	Computer Aided Design	*k*	Machining constant
SCS	Solid Creation System	P	Total required power
SGC	Solid Ground Curing	P_0	Idle power
FDM	Fused Deposition Modeling	E_{total}	Total energy consumption
LOM	Laminated Object Manufacturing	$E_{machine}$	Idle energy consumption
3DP	3-Dimensional Printing	$E_{sintering}$	Consumed energy for sintering
MJS	Multiphase Jet Solidification	$P_{machine}$	Unit power
BPM	Ballistic Particle Manufacturing	$P_{sintering}$	Required power for sintering
SLS	Selective Laser Sintering	$\Delta t_{machine}$	Total time
SLM	Selective Laser Melting	$\Delta t_{sintering}$	Total time for sintering
CNC	Computer Numerical Control	STEP	Standart for the Exchange of Product Model Data
SFF	Solid Freeform Fabrication	STEP AP224	An application protocol located in the ISO 10303
SL	Stereolithography	$E_{cutting}$	Consumed energy for cutting

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References

[1] **Wang, X.C., Laoui, T., Bonse, J., Kruth, P., Lauwers, B., Froyen, L., (2002)**, "Direct selective laser sintering of hard metal powders: experimental study and simulation", Int J Adv Manuf Technol, No.19, pp 351–357.

[2] **Tang, Y., Loh, H.T., Fuh, J.Y.H., Wong, Y.S., Lee, S.H., (2005)**, "An algorithm for disintegrating large and complex rapid prototyping objects in a CAD environment", Int J Adv Manuf Technol, No.25, pp 895–901.

[3] **Luo, Y., Ji, Z., Leu, M.C., Caudill, R., (1999)**, "Environmental performance analysis of solid freeform fabrication processes", Proceedings of the 1999 International Symposium on Electronics & the Environment, Danvers, MA, pp 1-6.

[4] **Sreenivasan, R., Bourell, D.L., (2009)**, "Sustainability study in selective laser sintering" Proceedings of the 2009 solid freeform fabrication symposium, University of Texas, Austin, pp 257-265.

[5] **Mognol, P., Lepicart, D., Perry, N., (2005)**, "Rapid prototyping: energy and environment in the spotlight", Rapid Prototyping Journal, No.12(1), pp 26-34.

[6] **Yadroitsev, I., Gusarov, A., Yadroitsava, I., Smurov, I., (2010)**, "Single track formation in selective laser melting of metal powders", Journal of Materials Processing Technology, No.210, pp 1624–1631.

[7] **Kellens, K., Dewulf, W., Overcash, M., Hauschild, M., Duflou, J.R., (2012)**, "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", The International Journal of Life Cycle Assessment, No.17(1), pp 69-78.

[8] **Baumers, M., Tuck, C., Hague, R., Ashcroft, I., Wildman, R., (2010)**, "A comparative study of metallic additive manufacturing power consumption", Proceedings of the Solid Freeform Fabrication (SFF) Symposium, The University of Texas, Austin, pp 278-288.

[9] **Baumers, M., Tuck, C., Wildman, R., Ashcroft, I., Hague, R., (2011)**, "Energy inputs to additive manufacturing: does capacity utilization matter?", Proceedings of the Solid Freeform Fabrication (SFF) Symposium, The University of Texas, Austin, pp 30-40.

[10] **Baumer, M., (2012)**, "Economic aspects of additive manufacturing: benefits, costs and energy consumption", Doctoral Thesis, Loughborough University, United Kingdom.

[11] **Gutowski, T., Dahmus, J., Thiriez, A., (2006)**, "Electrical Energy Requirements for Manufacturing Processes", Proceedings of 13th CIRP International Conference of Life Cycle Engineering, Lueven.

[12] **Wang, R.J., Wang, L., Zhao, L., (2007)**, "Liu Zinfluence of process parameters on part shrinkage in SLS", Int J Adv Manuf Technol, No.33, pp 498-504.

[13] **Boilat, E., Kolossov, S., Glardon, R., (2004)**, "Finite element and neural network models for process optimization in selective laser sintering" Proc Inst Mech Eng B J Eng Manuf, No.218, pp 607-614.

[14] **Sachdeva, A., Singh, S., Sharma, V.S., (2013)**, "Investigating surface roughness of parts produced by SLS process", Int J Adv Manuf Technol, No.64, pp 1505-1516.

[15] Martello. The process schema of selective laser sintering. http://www.martello.co.uk/rapid_prototyping.htm (accessed 30.12.2015)

[16] **Amaitik, S.M., (2005)**, "Development of a step feature-based intelligent process planning system for prismatic parts" Doctoral Thesis, Middle East Technical University, Mechanical Engineering, Ankara.

[17] AZO Materials. Density of Grade 23 Ti-6Al-4V ELI Alloy. http://www.azom.com/article.aspx?ArticleID=9365 (accessed 01.01.16)

[18] **Moradnazhad, M., (2015)**, "Energy Consumption Modeling of Turn-Mill Systems and Related Machining Processes", M.S. Thesis, Middle East Technical University, Mechanical Engineering, Ankara.

[19] **Rajemi, M.F., (2010)**, "Energy Analysis in Turning and Milling", Dr. Thesis, The University of Manchester School of Mechanical, Aerospace and Civil Engineering, Manchester.

[20] **Kalpakjian, S., Schmid, S.R., (2010)**, Manufacturing Engineering and Technology, Prentice Hall, Malesia.