EDUCATIONAL MODULE ON SUSTAINABLE ADDITIVE MANUFACTURING (AM)

Instructor Overview

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The instructor can use this document to gain general information about the available materials in this Educational Module. It also contains the homework solution manual in Annex A, below.

The educational module includes the following files, which are discussed in the sections below:

1. MT1- COURSE ELEMENTS - AM - 1 Overview (MS Word)
2. MT1- COURSE ELEMENTS - AM - 2 Intro Sust Mfg (MS PowerPoint)
3. MT1- COURSE ELEMENTS - AM - 3 Into to Additive Mfg (MS PowerPoint)
4. MT1- COURSE ELEMENTS - AM - 4 Energy Analysis (MS PowerPoint)
5. MT1- COURSE ELEMENTS - AM - 5 Future Trends (MS PowerPoint)
6. MT1- COURSE ELEMENTS - AM - 6 Homework (MS Word)
7. MT1- COURSE ELEMENTS - AM - 7 Laboratory (MS Word)

MT1- COURSE ELEMENTS - AM - 1 Overview (MS Word)

The instructor can use the Course Elements document to gain more insights about the goals, outcomes, and resources (e.g., instructional and active learning) related to this module. The document includes introduction, rationale (improving additive manufacturing for ensuring sustainable engineering), course content (theory, methodology, and applications), connections to existing core curricula, a case study, references for further reading, and instructions for lectures.

MT1- COURSE ELEMENTS - AM - 2 Intro Sust Mfg (MS PowerPoint)

The instructor can use this slideset to teach students basic definitions in sustainable engineering. The learning outcomes are as follows:

* Define sustainability, sustainable engineering, and sustainable design and manufacturing
* List the three pillars of sustainability
* Give an example of ways that engineers can contribute to a sustainable future
* Give examples of sustainability indicators/metrics for engineering decision making

MT1- COURSE ELEMENTS - AM - 3 Into to Additive Mfg (MS PowerPoint)

The instructor can use this slideset to teach students basic definitions of additive manufacturing. The learning outcomes are as follows:

* Understand the role of additive manufacturing processes in advanced manufacturing development
* Learn to calculate the part build time in additive manufacturing

MT1- COURSE ELEMENTS - AM - 4 Energy Analysis (MS PowerPoint)

This slideset can help the instructor in teaching additive manufacturing process evaluation. The learning outcomes are as follows:

* Understand the importance of energy evaluation of a process
* Analyze the energy and cost of producing a part using additive manufacturing process

MT1- COURSE ELEMENTS - AM - 5 Future Trends (MS PowerPoint)

This slideset can help the instructor in teaching potential future paths in additive manufacturing. The learning outcomes are as follows:

* Understand the development curve for additive manufacturing processes
* Identify research and development opportunities for promoting additive manufacturing as a main stream manufacturing technique

MT1- COURSE ELEMENTS - AM - 6 Homework (MS Word)

The instructor can use this document to evaluate student learning. This document encompasses two parts. Part I has six main questions (conceptual, short answer, and calculation questions). Part II includes description for an in-class discussion. Students would need to prepare prior to class and present on their topic of research during class. The solutions for questions in Part I are provided in Annex A, below.

MT1- COURSE ELEMENTS - AM - 7 Laboratory (MS Word)

The instructor can use this document as an active learning resource to aid in improving student learning by immersing them into the course materials through two different activities. The purpose of the laboratory case study is to evaluate the energy utilized in an additive manufacturing process, and improve its energy performance through informed product and process decision making. This document serves as an instructional guide to help users understand and navigate the developed energy analysis method. During the two lab activities, students will design and build a keychain using FDM (fused deposition modeling) machine. The document provides a detailed list of instructions to help students obtain the input data required for analyzing the energy and cost of the FDM process.

Annex A – Homework Solutions

1. Briefly discuss the following concepts. Include at least one reference (website, textbook, journal articles, etc.) in your response:
   1. Sustainability Engineering

The student may choose to present this discussion in various ways. For example:

“Design of human and industrial systems to ensure that humankind’s use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment.” (Mihelcic et al., 2003)

* 1. Advanced Manufacturing

The student may choose to present this discussion in various ways. For example:

“Use of innovative technologies to create existing products and the creation of new products. Advanced manufacturing can include production activities that depend on information, automation, computation, software, sensing, and networking.” (www.manufacturing.gov)

* 1. Additive Manufacturing

The student may choose to present this discussion in various ways. For example:

American Society for Testing and Materials (ASTM) committee F42 defined additive manufacturing as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.”

1. List and define the three pillars of sustainability. Provide three metrics that can be used to measure the performance of each of the three pillars (nine metrics total).

Environmental: This pillar relates to plants, animals, air, land, and water, and other aspects related to the natural environment (example metrics: greenhouse gas emissions, primary energy use, land disruption).

Social: This pillar relates to people, society, and societal organizations (example metrics: employment rate, health risks, income level, government programs).

Economic: This pillar relates to industry, technology, and economic systems (example metrics: profits, export potential, import penetration).

1. Identify three key limitations of additive manufacturing and discuss how these can be addressed by future research. Include at least three references (website, textbook, journal articles, etc.) in your response.

Limitations identified may include: Improvements in surface finish; Increase in detail rendition by thinner layers; Improvements of material properties and range; Elimination of rework; Reduction of construction time; and Reduction of total cost. There are a number of ways these can be addressed, and responses can be evaluated against the supporting references provided by the student.

1. Find three new additive manufacturing applications that have been developed in the last year. Include your references (website, textbook, journal articles, etc.) in your response.

The student may choose to present this discussion in various ways based on their findings in literature.

1. A prototype of a keychain with a circular cross-section is to be fabricated using stereolithography. The radius of the outside dimension is 40 mm and the inside radius is 30 mm (ring thickness of 10 mm). The thickness (z-direction height) of the keychain is 10 mm and the layer thickness is 0.20 mm. The laser beam spot size is 0.5 mm. Assume beam is moved across surface at a velocity of 3000 mm/min. Compute an estimate for the time required to build the part, if 5 seconds are lost for each layer to lower the platform that holds the part. Neglect the time for post curing.

question 5 Solution:

Layer area, Ai, is the same for all layers.

Ai= π(40)2–π(30)2= 2199 mm2

Time to complete one layer Ti is the same for all layers.

Ti= (2199 mm2)/((0.5 mm)(50 mm/s)) + 5s = 87.96 + 5 = 92.96 s

ni= (10 mm)/(0.2 mm/layer) = 50 layers

Build time

Tbuild = (50 layers)(92.96 s/layer) = 4,648 s = 77.5 minutes

1. A company wants to produce 1000 toy connector blocks by using fused deposition modeling (FDM). The toy connector block design is shown in Figure 1. The major cost drivers to fabricate the blocks are materials and energy use. Engineers know that build time is a major factor to reduce energy use. Thus, they developed a process model to estimate build time (Tbuild), where V is the volume of the part, SA is the surface area, and C1, C2, C3, and C4 are model constants, as shown in Eq. 1.

(1)

The values for C1, C2, C3, and C4 are 2.8625x10-4, 9.6791x10-1, 2.4636x10-6, and 12.5292 respectively. The FDM machine has a rated power (PFDM) of 10 kW. Assume that the company buys electricity at the rate of 10 cents/kWh in completing the analysis below.

* 1. Calculate the total process energy. Determine the energy and material costs for manufacturing 1,000 toy blocks from ABS, which has a density of 1.07 g/cm3 and costs $100/kg.
  2. Calculate the post processing energy cost if the block design has a shape complexity (SC) value of 2. The post processing machine rated power (Ppost) is 1 kW. Assume that the parts are washed in batches of 10. The base washing time (tbase) is 30 seconds, the base area (Abase) is 2 cm2, and K1, K2 and K3 are 1, 1, and 0, respectively.

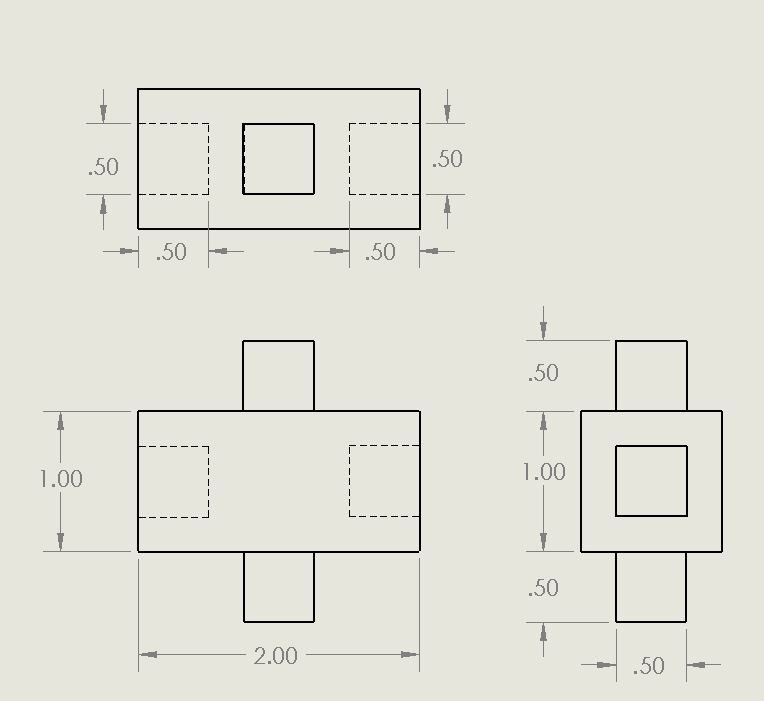


Figure 1: Toy Connector Block Design

Question 6 Solution:

The total surface area of the block (SA)

SA= Total area of rectangular block + Area of square blocks + Sum of internal face area

= [(4\*2 cm2 + 2\*1 cm2) – 4\*(0.25 cm2)] + 2\* (5\*0.25 cm2) + 10\*(0.25 cm2) = 14 cm2

The total volume of the block (V)

V = Volume of rectangular block + Volume of square blocks – Volume of internal holes

= (2cm\*1cm\*1cm) + 2\*(0.5cm\*0.5cm\*0.5cm) - 2\*(0.5cm\*0.5cm\*0.5cm) = 2 cm3

The total build time of the block (Tbuild)

Tbuild = C1\*V4 + C2\*SA –C3\*V4\*SA + C4

= (2.8625E-4\*24) + (9.6791E-1\*14) – (2.4636E-6\*24\*14) + 12.5292 = 26.08 mins

The total time for building 1000 blocks

1000 blocks \* 26.08 min/block = 26,080 mins = 434.7 hrs.

The total volume of ABS material required for building 1000 parts

1000 blocks \* 2 cm3/block = 2,000 cm3

The total mass of ABS material used for 1000 blocks

2000 cm3 \* 1.07 g/cm3 = 2,140 g = 2.14 kg.

**Part a)**

The total machine (process) energy (EFDM)

EFDM = PFDM \* Tbuild = 10 kW \* 434.7 hr. = 4,347 kWh

The total machine energy cost (CFDM)

CFDM = EFDM \* Cost of electricity = 4,347 kWh \* $0.10/kWh = $434.7

The total material cost (CABS)

CABS = Total material mass \* Material unit cost = 2.14 kg \* $100/kg = $214

**Part b)**

The post processing time (Tpost)

Tpost= tbase + SC \* {tbase + [K1 \* tbase \* (SA/Abase)] + (K2 \* tbase \* Ni) + (K3 \* tbase \* Ai)}

= 0.5 + 2 \* {0.5 + [1 \* 0.5 \* (14/2)] + (1\*0.5\*2) + (0\*0.5\*0.25)} = 10.5 min.

The total post processing time for 1000 blocks = total post processing time for 100 batches=

100 batches \* 10.5 min/batch = 1050 mins = 17.5 hrs.

The total post process energy (Epost)

Epost = Ppost \* Tpost = 1 kW \* 17.5 hr = 17.5 kWh

The total post processing energy cost (Cpost)

Cpost = Epost \* Electricity cost = 17.5 kWh \* $0.10/kWh = $1.75