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Additive Manufacturing and High Speed Machining -Cost comparison of short lead time manufacturing methods

Sebastian Hällgren[a,b], Lars Pejryd[b], Jens Ekengren[b]

[a]*Saab Dynamics, Development, 69180 Karlskoga, Sweden*
[b]*School of Science and Technology, Örebro Univeristy, Sweden*

* Corresponding author. Tel.: +46 734461231; *E-mail address:* sebastian.hallgren@saabgroup.com

Abstract

Additive Manufacturing (AM) using Powder Bed Fusion (PBF) allows part with abstract shapes, that otherwise would need costly tooling, to be manufactured with short lead time. In this study AM build time simulations are used to predict series part cost for eight parts that are possible to cut from rod blanks using High Speed Machining (HSM). Results indicate that when the part shape can be cut from rod blanks, AM is more expensive than HSM even for series of one. If post processing machining is added to the printed AM blank part, the cost difference increases further. Finally, the model is used to predict part-cost in series production if print speed increases, if machine cost is reduced or if part mass is reduced as a result of redesign for AM.

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1. Introduction

Additive Manufacturing or 3D-printing in metals makes it possible to manufacture shapes that previously were impossible to manufacture or could only be realised using long lead time tool based manufacturing methods. When series volume is low and Non-recurring cost (NRC) is large due to tooling, the per-part cost increases. Parts and products that have uncertain series volumes or high form requirements may be realised both during development and in series production using High Speed Machining. HSM is similar to AM as it manufactures parts with low tooling costs and short lead times. Low lead time manufacturing such as High Speed Machining or Additive Manufacturing is favourable for series production in lower volumes. During development, fewer parts are needed but sooner in order to reach the market quicker, and to reduce concurrent engineering team development cost. Geometrical changes, more common during development, are usually both faster and cheaper to accommodate when retooling is not needed.

High Speed Machining is a subtractive manufacturing method involving high feed rates and high spindle turning speeds that lowers torque and decreases tool temperature. Depending on part shape and machine, special or standardised fixtures are needed to hold the work piece steady in place. Today, most machines are numerically controlled (NC) and programmed using a 3D-model as input to plan toolpaths. In many cases, the first manufactured part may be delivered to the customer as the workflow is robust and well known. Blanks for machining may be standard rod blanks or cast or wrought parts in need of cutting to tolerances. The material removal rate (MRR) is determined by the material toughness in addition to part shape. A Machinability Rating (MR) has been established by AISI to relatively compare different materials cost to cut. The rating includes cost effects of MRR and tool wear. An AISI rating of 1.00 is assigned to a cold drawn steel B1112 with Brinell hardness of 160. Values lower than 1.00 indicates a more expensive to cut material and higher values means it is nominally a cheaper material to cut. Design guide lines for HSM inform a designer what shapes and features to avoid and which of them drives cost.

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3D printing or Additive Manufacturing has been around for about 30 years and was initially used to produce plastic prototype or mock-up parts during development. An energy source melts deposited powder layer by layer on a moving platform. Typical metal Powder Bed Fusion AM machine costs are close to 1M Euro. Major cost contributors are large part height that combined with small layer thicknesses causes long build times in an expensive machine. A trade-off scenario for lowest possible part cost exists between choosing build direction for low height, the resulting build volume utilisation and support structure build up and cost of removal. Most parts are post processed after print. Post processing often includes heat treatment and surface roughness adjustment. If the as-printed part dimensional requirements cannot be met by the printed surface, machine cutting is needed. Allowance material is needed to be added prior to building an AM blank similar to other near net shape manufacturing methods.

The possibility to manufacture abstract and complex shapes is perhaps the most obvious benefit of AM. Gibson et al. defines terms as shape complexity, material complexity, hierarchical complexity and functional complexity to describe areas where AM adds to existing manufacturing methods [1]. Klahn et al. defines four areas where additive manufacturing might be advantageous; integrated design, individualisation, lightweight design and efficient design [2]. Yau et al. compared dental prosthetics manufactured using AM and 5-axis milling and shortly states that AM is costlier [3]. Yoon et al. compared energy consumption of additive and subtractive methods. They found that injection moulding was 100 times more productive than AM, and the same applied for the Specific Energy Consumption (SEC) per part produced [4]. Faludi et al. did an environmental impact comparison between plastic Filament Depositon Modelling (FDM) parts versus milling and states that for FDM electricity had the largest environmental impact and for subtractive manufacturing material waste and cutting fluids were the largest, suggesting that FDM is better than milling from environmental impact [5]. Atzeni et al. shows result of a reengineering effort of an aircraft landing gear mechanism using both topology optimisation and part consolidation. They compare cost between AM and die casting finding that for less than 40 items AM was cheaper [6]. It is unclear if the time cost to reengineer the original design was included in the comparison.

Are parts that do not take advantage of the shape complexity that AM provides economically suitable for series production using AM? If not, how much faster or how much cheaper must metal PBF become to cost effectively produce simpler shapes using AM? What cost effect would a mass-reduction through topology optimisation have on a part produced in aluminium? Can print speeds derived from build simulation be used to predict print speeds for another material? To answer these questions, a cost comparison mathematical model has been created. It uses real part quotes and compares them to AM build time simulations.

Some differences between machining and AM are shown in table 1.

Table 1. High speed machining and additive manufacturing costs and strengths

	High Speed Machining, HSM	Metal Powder Bed Fusion
Cost drivers	Number of operations, Material Removal Rate MRR, volume removal	Part height, part volume, support/heat structures during build
Lead time drivers	Rod blank availability, machine setup and planning	Machine setup, post processing needs on printed AM blank
Accuracy	~0.01mm	~0.1mm
Surface roughness	Very fine	Medium/rough
Ultimate strength	Aluminium: A Titanium: T	Aluminium: 0.5*A (Cast like properties) Titanium: T (wrought like properties)
Data input	3D model, NURBS, drawings	3D model, tessellated
Strengths	Low NRC, fine tolerances, fine surfaces, robust workflow, good/stable material properties, many service providers, many materials	Low NRC, shape complexity for free, short lead time for cast like shapes, standardised shape (powder) on material
Weaknesses	Costly for many small features Long lead time for exclusive materials in rod Cost reduction due to large volume limited	Large surface roughness Moderate tolerance achievement Slow manufacturing speed Low material availability Limited part size.

2. Method

A mathematical model based on real HSM price quotes of designer drawn prismatic parts in aluminium has been created. HSM cost quotes were separated into recurring cost and non-recurring cost. Recurring HSM costs consist of material cost and machine cutting cost. NRC for HSM consisted of NC path planning and fixture cost. Non-recurring costs for AM consist of AM build preparation, machine preparation and recurring cost includes print time and material. Costs are compared between AM and HSM for the number of parts that fit within an AM build volume. The powder deposit cost is then shared for all parts built at the same time, creating a NRC per build chamber for the AM parts; see figure 1 and table 2. Cutting time effect for HSM due to change in material is modelled by the use of a ratio between the two materials' AISI Machinability Ratings (AISI MR), see figure 3 and table 4. The AM cost is estimated through build time simulations using an EOS SLM M290 printer. Parts were placed 10mm above the build platform. The build volume is filled with parts oriented with a build direction that trades-off support structure build up vs. build chamber packing. All parts share the powder deposit cost for the build. Build time is simulated for three different materials; steel, titanium and aluminium. AM blank cost is calculated by multiplying printing time to an experience based template cost per machine plus powder cost. The model aims to predict print times for a part in a new material by scaling a simulated print time for a given material with the max print speed ratio from table 4. Post process machine cutting of the AM blanks was estimated by offsetting part surfaces with stricter tolerances +0.5mm for allowance. After studying this effect on some of the parts, a 25% volume removal need of allowance was established, see figure 2. Support structures keep the part attached to the build plate