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Resources and manufacturing technology evaluation of hybrid additive metal laminated tooling for forming

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Abstract. The rough surface finish caused by the stair step effect is the major drawback in the application of sheet metal laminates in rapid tooling. The application of laser metal deposition (LMD) and subsequent post-processing (milling, ball burnishing, and laser polishing) to reduce the stair-step effect in hybrid additive metal laminated forming tools was recently presented. In the present study, the energy consumption and manufacturing time of the hybrid process are compared with the conventional (milling plus hardening by heat treatment) as well as with full LMD and milled components. The hybrid process requires significantly less energy and manufacturing time compared to the LMD components. Since the surface hardness is sufficient for tooling in the hybrid process, no additional hardening is required, also resulting in a shorter manufacturing time and lower energy relative to the conventional method (depending on the part mass, a minimum of 29% is faster). The optimal sheet laminate combination based on the economic criteria for the tool with a radius of 6 mm is presented.

Nomenclature

Symbol	Unit	Description	Symbol	Unit	Description
E	MJ	Energy consumption	C_L	mm	Cutting length
a	mm	Length of square part	X	-	Mass ratio of final part to the initial
d	mm	Diameter of cylindrical hole	T	s	Process time
c	-	Ratio of thickness to length	ρ	kg/mm^3	Density
t	mm	Sheet thickness	SEC	MJ/kg	Specific energy
n	-	Number of sheet layers	Q	mm^3/min	Material removal rate
m	kg	Mass of part	f	mm/min	Feed rate
a_e	mm	Radial depth of cut	P_L	W	Laser power
V	mm^3	Volume of stair step	a_p	mm	Axial depth of cut

Introduction

Metal sheet lamination or layer laminate manufacturing (LLM) as a rapid tooling method was patented for show molds in 1942 by Hart F.V [1]. For several years, different industries, especially the automotive industry, showed high-interest beginning in the 1980s [2]. However, the main drawback of the LLM method is the segregated surface, named the stair step effect, due to the stacking of sheets with different thicknesses to build a defined radius or angle. There are various methods for reducing the stair step effect in forming tools made of sheet metal laminates. The state of research in this area (use of a flexible intermediate layer [3], chamfering the corner of the laminae [4], machining of the laminae [5], ball burnishing [6], brazing or soft soldering [7]) is

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already summarized [8]. In [8], the stair step effect was reduced using laser metal deposition (LMD). Based on the DIN EN ISO/ASTM 529000 [9], direct energy deposition (DED) is a subcategory of the additive manufacturing (AM) process in which concentrated energy is applied to the filling material. LMD is also a DED process in which a laser is used as an energy source and metal powder as the filling material. The main advantage of the application of LMD is that the manufactured tool does not require an additional hardening process. The local heating of the surface during LMD, compared to heating the entire part for hardening in conventional manufacturing, can result in significant energy savings. In [8], three post-processing processes (milling, ball burnishing, and laser polishing) have been explored to produce an improved surface. By milling, the extra material is machined from the deposited surface. In ball burnishing, the surface roughness is improved by plastic deformation. Laser polishing involves re-melting the surface with a laser (without additional powder) to improve the roughness. It is shown that the post-processing by ball burnishing can improve the tool's hardness; however, the best surface roughness is achieved by milling.

In the following, the economic aspect of the introduced hybrid additive laminated tooling concept is compared with the conventional method (milling followed by hardening) and with the fully deposited part by LMD, which is milled afterward to improve the surface roughness. In addition, an approach to identify the optimum sheet combination is provided.

Procedure and Methodic

Sheet lamination offers the possibility of combining different sheet thicknesses. As shown in Fig. 1, the number of possible sheet combinations with three sheet thicknesses 0.5, 1, and 2 mm increases exponentially with increasing radius. The selection of the proper combination is a multi-objective optimization depending on the required tool strength, energy consumption, cost, and placement of functional elements, e.g., sensors, heating, or cooling channels. This study will lower the number of possibilities based on energy consumption and manufacturing time.

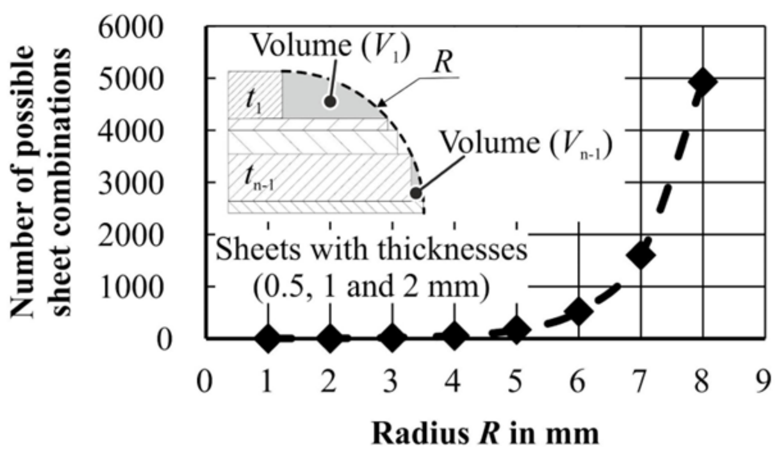

Fig. 1. Number of the possible sheet combinations for different radii with 0.5, 1, and 2 mm sheet thicknesses.

For systematic evaluation, it is necessary to define the process route of each method. As shown in Fig. 2, the hybrid additive laminated tooling starts with manufacturing the sheets. The sheets are laser-cut in different thicknesses and stacked based on the proper order. Next, the stair step areas (volumes) are filled with LMD, followed by post-processing.

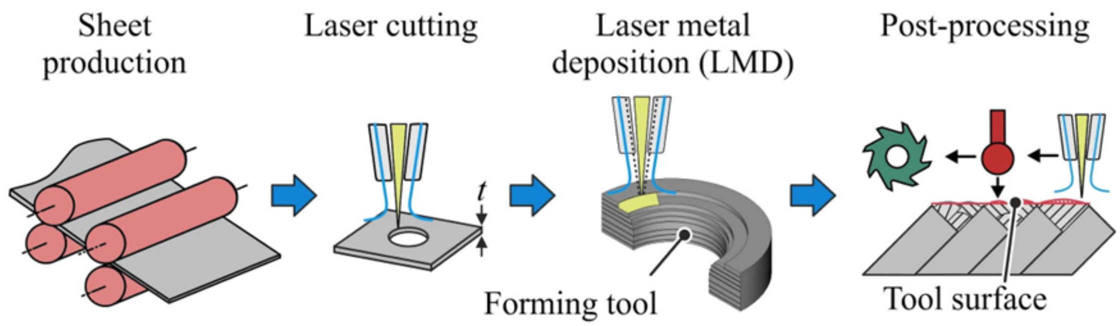

Fig. 2. Process route of hybrid additive laminated tooling.

For the calculation of the total energy consumption of hybrid additive laminated tooling (E_T^H) as shown in Eq. 1, the energy of sheet production (E_S), cutting energy by laser (E_C), required energy for the production of powder (E_P), and deposition (E_D) during LMD, and finally, the energy consumption during post-processing (E_{PP}) are considered.

$$E_T^H = E_S + E_C + E_P + E_D + E_{PP} \quad (1)$$

For the energy consumption of the conventional method (E_T^C), only the production energy for bulk material (E_B), milling (E_M), and hardening (E_H) are studied, as seen in Eq. 2:

$$E_T^C = E_B + E_M + E_H \quad (2)$$

To calculate the energy consumption of a fully deposited part by LMD with milling (E_T^{LMD}) as post-processing, the powder production (E_P), deposition (E_D), and milling (E_M) energies are taken into account (see Eq. 3).

$$E_T^{LMD} = E_P + E_D + E_M \quad (3)$$

For the estimation of the production time (T) for each process (hybrid, conventional, and fully LMD), the manufacturing time of the sheet, bulk material, and powder production are not considered.

Hybrid additive laminated tooling.

Since the manufacturing energy and time for a systematic evaluation strongly depend on the part geometry, it is assumed that an academic square part with length a and with a cylindrical hole with diameter d has to be manufactured (Fig. 3a). The ratio c is defined as the thickness of the part as a fraction of the length. In the hybrid process, it is assumed that the part is made from n sheets with a constant thickness t (Fig. 3b). The same geometry is used for the calculations for the conventional and fully LMD parts.

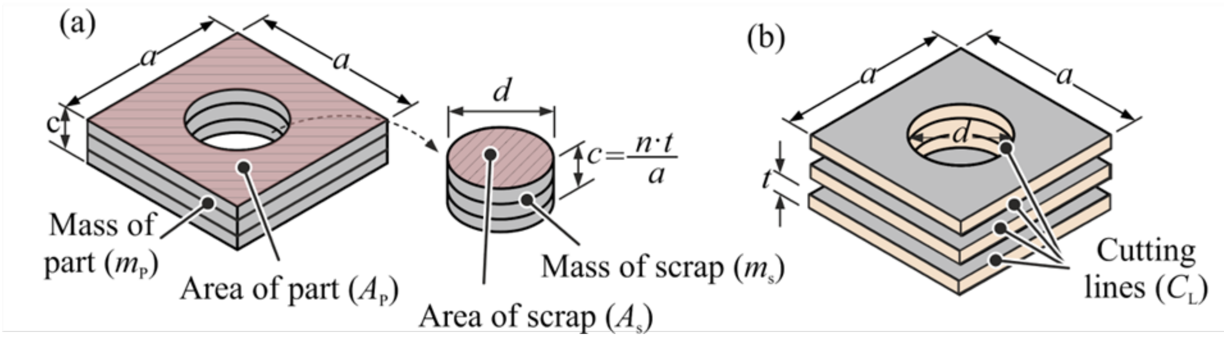

Fig. 3. (a) Assumed geometry for calculations (b) cutting length (C_L).

The mass ratio (X) is defined as the mass of the final part (m_P) to the mass of the initial state ($m_P + m_s$) as shown in Eq. 4. By taking into account that all the used sheets have an equal density (ρ), the mass ratio (X) can be defined as a ratio of final part surface (A_P) to the total initial surface ($A_P + A_s$), as illustrated in Fig. 3a. It yields the relation of the length of the square (a) and hole diameter (d) as provided in Eq. 4.

$$X = \frac{m_P}{m_P+m_S} = \frac{A_P}{A_P+A_S} = 1 - \frac{\pi d^2}{4a^2} \Rightarrow d = a \cdot \sqrt{\frac{4(1-X)}{\pi}} \tag{4}$$

Considering volume constancy, the length of the square (a) can be determined as:

$$c \cdot a^3 = \frac{m_P}{X\cdot\rho} \Rightarrow a = \sqrt[3]{\frac{c\cdot m_P}{X\cdot\rho}} \tag{5}$$

For the determination of the energy required for laser cutting, it is required to compute the cutting length (C_L) of sheets (Fig. 3b). The cutting length (C_L) is the sum of the perimeter of the square and the hole as provided in Eq. 6. Replacing the Eq. 4 and 5 in the Eq. 6 yields the cutting length (C_L) as a function of the material yield ratio (X), density, sheet thickness, and final part mass:

$$C_L = (4a + \pi d)n\; n = \frac{ca}{t} \Rightarrow\; (4a + \pi d)\frac{c.a}{t} = \frac{1}{4t}(\frac{c\cdot m_P}{X\cdot\rho})^{\frac{2}{3}} \cdot \left(\sqrt{4\pi(1-X)} + 4\right) \tag{6}$$

The cutting length is calculated for three sheet thicknesses (Fig. 4a). It is concluded that the thinner the sheet thickness, the higher the cutting length for the same final part mass. For calculating the energy required for the laser cutting, the cutting information of the laser machine, model TC1005 from the company Trumpf, is used. Three steel sheets with a thickness of 0.5, 1.0, and 2.0 mm are used for the calculations. The feed rate for cutting the sheets with thicknesses 0.5, 1.0, and 2.0 mm are 9, 8, and 5 m/min, respectively. A laser power of 1700 W is required for cutting 0.5 and 1.0 mm sheets and 1200 W for 2 mm sheets. The total energy consumption of the machine for laser cutting the 0.5 and 1.0 mm sheets equals 42 kWh and 38 kWh for 2 mm sheets [10]. The cutting time can be calculated based on the cutting length (C_L) and feed rate during cutting. Afterward, the total energy consumption for laser cutting (E_C) can be calculated for different steel sheet thicknesses, as shown in Fig. 4b, assuming the density of steel (ρ) is 7900 kg/m^3. It can be seen that for the same final part mass, the thicker sheet thickness requires lower energy for cutting.

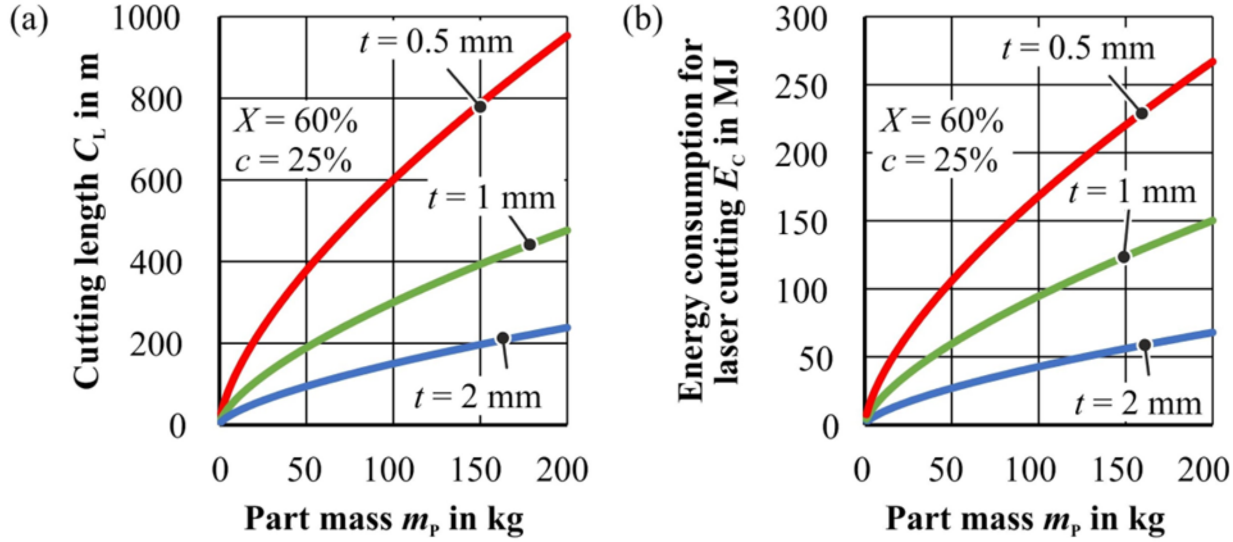

Fig. 4. (a) Cutting length, C_L (b) cutting energy with TC1005 machine.

Based on [11], the production of a 1 kg sheet requires 19.37 MJ of energy. Therefore, the required energy for sheet production (E_S) is equal to 19.37 [MJ/kg] · ($m_P + m_s$). The energy required for the production of the powder differs depending on the production method. According to [12], for producing the powder by gas atomization, 24.48 MJ/kg of energy is needed. In the hybrid method, it is assumed that the mass of the sum of the stair step volumes ($m_{\text{Step}} = \rho \cdot \sum_{i=1}^{n-1} V_i$), see Fig. 1, is 1% of scrap mass (m_S), i.e. the required powder by laser metal deposition (LMD) is 1% of m_S. The required powder energy production (E_P) for hybrid additive laminated tooling is E_P = 0.2448 [MJ/kg] · m_S. The deposition energy consumption with Lasertec 65 3D machine from the company DMG MORI as reported by [13], is 76.11 MJ/kg. By considering 1% of the scrap mass, the deposition energy for the hybrid method is E_D = 76.11 [MJ/kg]· (0.01m_S) or E_D = 0.7611 [MJ/kg] · m_S.

Since only the sheet thickness of 1 mm will be considered in the rest of the calculations, it is assumed that the track distance during the post-processing is 1 mm and that for ball burnishing and laser polishing, the tool moves through the whole cutting length (C_L). The essential energy required for ball burnishing is considered based on the Ecoroll hydraulic aggregator HGP6.5, which is $E_{Ep.}^{B} = 3\ kW$. For laser polishing, the laser power during the polishing is considered as essential energy consumption ($E_{Ep.}$), where $E_{Ep.}^{L} = 1000$ W. The energy required for post-processing for the hybrid method (E_P^H) by ball burnishing and laser polishing is $E_P^H = T_P^H \cdot E_{Ep.}$, where T_P^H is the post-processing time. To compute the energy required for milling, the specific energy of finishing (SEC_F) from [14] is used, i.e. SEC_F = 5.79 MJ/kg. It is assumed that 20% of the deposited material (1% of m_S) needs to be milled. Therefore, the required energy is:

$$E_{PP}^{Hybrid} = 0.2 \cdot 0.01 \cdot m_S \cdot SEC_{Finishing} = 0.01158\ [MJ/kg] \cdot m_S \quad (7)$$

To determine the milling time, the radial depth of cut (a_e) and axial depth of cut (a_P) need to be defined to calculate the material removal rate $Q = f \cdot a_P \cdot a_e$ where f is the feed rate of the cutting tool. Therefore, the milling time is calculated as $T_M^H = \frac{Q_F^H}{0.01 \cdot m_S}$.

Conventional method.

For the production of bulk materials per kg, according to [15], 17.73 MJ of energy is required. This value is used to calculate the total energy required for producing bulk material in the conventional method:

$$E_{Bulk} = 17.73\ [MJ/kg] \cdot (m_P + m_s) = \frac{17.73}{X} \cdot m_P \tag{8}$$

The milling process is divided into two steps: rough milling and finishing. The specific energy (SEC_R) for rough milling is 0.848 MJ/kg [14]. The 99% of the scrap mass must be rough-milled, and the rest should be machined by finishing. The total energy and production time for the milling of the conventional method are calculated as shown in Eq. 9:

$$E_M^C = \left(0.99 \cdot SEC_R\ + 0.01 \cdot SEC_F\ \right) \cdot m_s\ = 0.8974\ \left[\frac{MJ}{kg}\right] \cdot m_s\ and\ T_M^C = \frac{Q_F^H}{0.01 \cdot m_s} + \frac{Q_R^H}{0.99 \cdot m_s} \tag{9}$$

The energy consumption of the hardening process is significantly dependent on the type of hardening and furnace type. In this study, the furnace N120/85 HA from the company Nabertherm with an energy consumption of 13.6 kWh, is used for the calculations. It is assumed that the part will be quenched at 850 °C. According to [16], the required time for heating a part with a thickness of 80 mm is one hour. Considering the thickness of 80 mm and the thickness-to-length ratio (c) of 25% (see Fig. 2a), the length of the square (a) is calculated to be 320 mm. For steel, the corresponding weight will be approximately 64.7 kg. Considering the hour of homogenizing time, the required energy and time are evaluated as shown in Eq.10. Here, it is considered that during the homogenizing, the furnace works with 50% of its maximum power. It is noted that 1 kWh equals 3.6 MJ.

$$E_H^C\ = \frac{\left(13.6+\frac{13.6}{2}\right)kWh}{64.7\ kg} \cdot 3.6 \frac{MJ}{kWh} \cdot m_{P.} = 1.14\ \cdot m_P\ \ and\ T_H^C\ = \frac{2\ h}{64.7\ kg} \cdot m_P\ = 0.031 \cdot m_P \tag{10}$$

Fully deposited part (LMD plus milling).

For calculating the energy consumption of fully LMD parts followed by milling, the extra powder is required to be considered. This powder is waste material discharged during the positioning of the nozzle. This value is assumed as 20% of the final part mass. With this, the energy consumption for the powder production for the fully LMD part and the required energy during the deposition are:

$$E_P^{LMD} = 24.48 \left[\frac{MJ}{kg}\right] \cdot (0.2 \cdot m_P) = 4.896\ \left[\frac{MJ}{kg}\right] \cdot m_P\ \ and\ E_D^{LMD} = 76.11 \left[\frac{MJ}{kg}\right] \cdot m_P \tag{11}$$

Considering the 1% of the part mass that needs to be milled, the required energy and time for the conventional method are:

$$E_M^{LMD} = 0.01 \cdot SEC_F\ \cdot m_{P.} = 0.0579 \left[\frac{MJ}{kg}\right] \cdot m_P\ and\ \ T_M^{LMD} = \frac{Q_F^{LMD}}{0.01 \cdot m_P} = \frac{\rho \cdot f \cdot a_p \cdot a_e}{0.01 \cdot m_P} \tag{12}$$

Results and Discussion

The energy consumption and manufacturing times are calculated based on the equations provided in the previous section and considering the following process parameters for the different processes in Table 1.

Table 1. Process parameters for milling, laser polishing, and ball burnishing.

Process	Laser polishing	Ball burnishing	Milling	
			Rough	Finishing
Feed rate f in [mm/min]	1000	900	600	200
Laser power P_L in [W]	1000	-	-	-
Radial depth of cut a_e in [mm]	-	-	25	25
Axial depth of cut a_p in [mm]	-	-	2	0.25

The total energy consumption for all three processes is shown in Fig. 5. It shows that the fully deposited method (LMD plus milling) has a very high energy consumption compared to the hybrid and conventional methods. It can be seen that there is no significant difference between the hybrid and the conventional method. Also, there is no significant difference between the different post-processing methods since the post-processing portion of the total energy consumption of the hybrid method is insignificant.

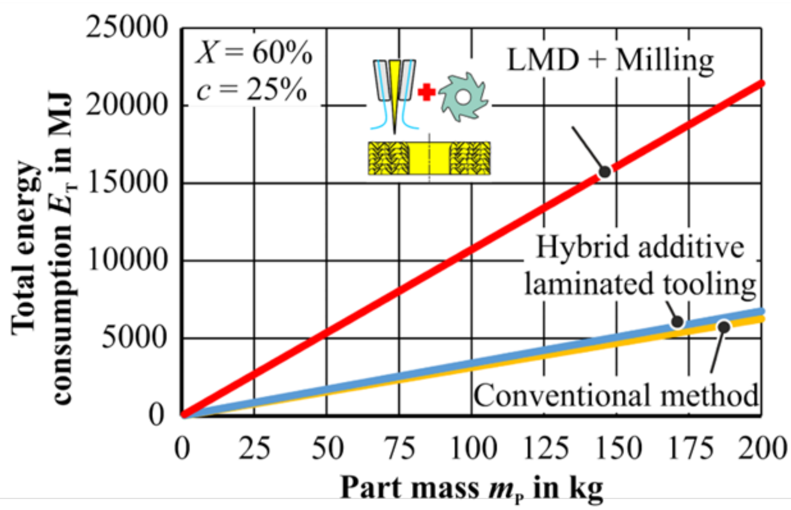

Fig. 5. Comparison of total energy consumption between hybrid, conventional, and fully LMD with the milling method.

The calculated manufacturing time for all three processes in Fig. 6a shows that fully deposited parts require a very high manufacturing time compared to the hybrid and conventional methods. The conventional method has a higher manufacturing time, even without considering the part transportation for hardening, than the hybrid method, as shown in Fig. 6b.
Between the different post-processing methods, the milling shows a shorter time; however, the difference between ball burnishing and laser polishing is insignificant. Since the processing time highly depends on feed rate, track distance, and tool diameter, the order of post-processing would be different. It should also be considered that the advantage of using laser polishing as post-processing is saving the cost of new tools and programming time. Also, laser polishing is a contactless process, so there is no tool wear. Finally, the focal distance of the laser allows the treatment of limited access areas. However, as mentioned, the main drawback is the reduction of the hardness of the treated surface [8].

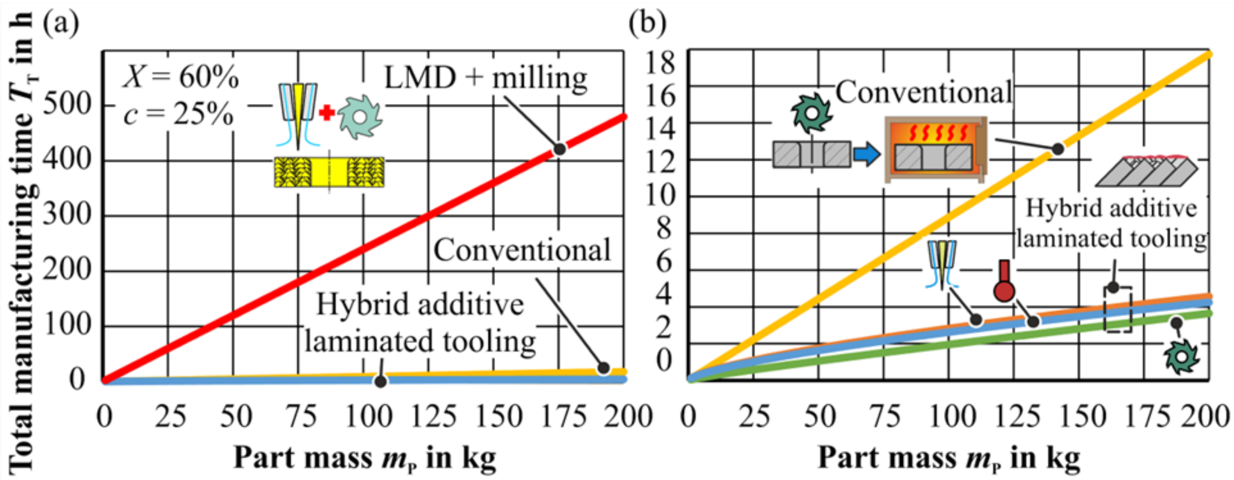

Fig. 6. Total manufacturing time (a) with LMD plus milling (b) without LMD plus milling.

As shown in Fig. 1, a high number of possible sheet combinations exist for each radius. Considering the same mechanical performance for all combinations, i.e. the tool strength is the same for all combinations, the number of sheet combinations can be limited by considering the energy, cost, and manufacturing time issues. For optimizing the sheet combinations, the following criteria are considered:

- The normalized laser cutting time (T_C^N),
- the normalized energy of production of metal powder and deposition energy ($E_P^N + E_{LMD}^N$),
- the normalized energy required for the laser cutting (E_C^N).

These factors (time and energy consumption) are desired to be kept as low as possible. For instance, for a radius of 6 mm, the energy and time are individually calculated and evaluated for all 520 combinations with different sheet thickness arrangements based on the mentioned criteria. The results are plotted in Fig. 7. It can be seen that the break-even point is around 0.33 for all criteria. Considering this value, the number of sheet combinations is reduced from 520 to 24.

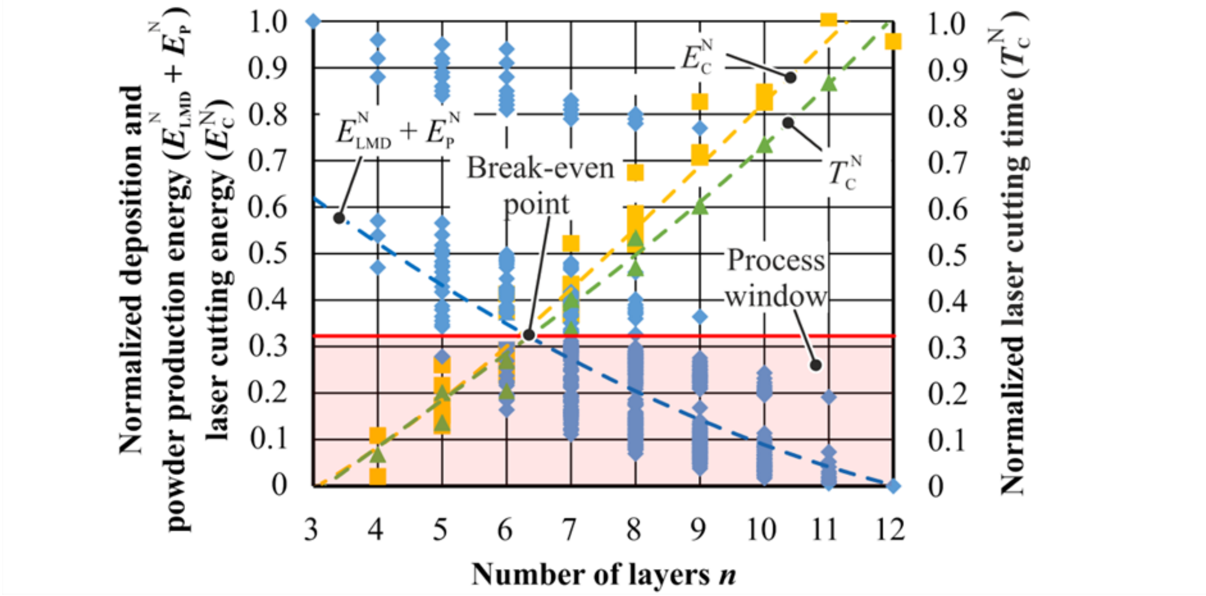

Fig. 7. Determination of break-even point for tool radius of 6 mm.

Summary
A systematic energy and manufacturing time evaluation of the introduced hybrid additive laminated tool manufacturing is provided. The results are compared with the conventional process route (milling followed by hardening) and also with a fully deposited part using laser metal deposition followed by milling as a post-processing method. The results show that the hybrid method is much more economical and faster than the fully deposited method and is comparable with the conventional method. However, the hybrid method is more suitable due to its ability to produce complex shapes in a shorter time. The production time depends considerably on the part geometry, but in this case the hybrid process is at least 29% (depending on the mass) faster than the conventional process. Laser polishing between the three post-processing methods provides an acceptable surface roughness without additional tooling costs and programming challenges compared to milling and ball burnishing but with lesser hardness (around 9% less as deposited). Since sheet lamination theoretically offers a high number of sheet combinations, the economic evaluation reduces the number of suitable sheet combinations for more effective manufacturing.

Acknowledgment
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