Laser-aided direct metal tooling of manufacturing aviation details on CNC machine

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Abstract. This paper discusses the effectiveness of the use of hybrid technology based on Laser-aided Direct Metal Tooling with subsequent machining as an alternative to traditional methods for producing products of a complex profile for the aviation industry. The aspects of the application of Laser-aided Direct Metal Tooling in the production cycles of manufacturing products passing through the final assembly operations are considered. The paper proposes an alternative manufacturing technology through the use of Laser-aided Direct Metal Tooling at the stage of design and technological study of the manufacturing cycles of individual assembly units. The objective function of ensuring high requirements for the accuracy of the relative position of the part in the assembly, reducing the mass and dimensions of the product, which is important for modern aviation systems. A technological solution is proposed to provide technical indicators of the objective function based on combining the advantages of laser, hybrid, and additive technologies in the working area of technological equipment. Considered technical solutions for the implementation of the proposed hybrid technology in the manufacture of critical parts of the aviation industry. The aspects of the production of parts are considered from the point of view of reducing the error in the relative position of the actuating surfaces of the product, an analysis is made of the machining errors in the process of the proposed production technology, with respect to the errors arising from traditional production cycles of parts of this type.

1. Introduction
Additive manufacturing (AM) is increasingly finding its use as an alternative to traditional technologies [1-6]. Additive technologies have been actively developed in the aviation industry. This is due to the complexity of the structures used and constantly growing technical requirements for parts. The advantage of AM is the possibility of reducing the length of the technological cycle of production, reducing the range of production equipment and tooling and increasing the economic indicators of cost, including by reducing the time to prepare for production of products. The greatest technical and economic effect is achieved in the production of complex, critical products, including the presence in the technological process of the final assembly operations to obtain the finished product. Due to the application of AM in technological cycles, it becomes possible to multiply reduce the mass of the designed part / assembly / product, while retaining all the technical requirements for the part (strength, hardness, wear, etc.). It becomes possible to control the properties of individual parts of a part through the use of various materials and their combinations with improved properties [7-14].

Blade units are one of the most important elements of modern aircraft engines. The main disadvantage of the blade nodes is that it makes composite to reduce the use of expensive materials. The
need to finish the assembly significantly increases the requirements for the accuracy of individual elements and ultimately leads to an increase in their cost. On the technical side, the clearances required for the assembly operation during further operation lead to a change in the balance of the assembly, high wear and tear of individual structural elements and, in the end, costly repair of the engine as a whole.

One of the solutions to this problem is the transition to a solid structure and surfacing of the working elements of the blades of the necessary material through the use of Laser-aided Direct Metal Tooling (DMT). In this case, it becomes possible to develop a hybrid technology, including DMT of the necessary elements and their subsequent processing on single unit of process equipment.

As a method of growing parts of AM for this hybrid manufacturing technology details considered is DMT, combined in single unit of equipment with metal-cutting process.

The paper discusses the technological aspects of the application of such a hybrid technology in relation to the process of manufacturing parts of the type "impeller".

2. Research methodology

According to the technical requirements for machining and assembly of parts of the type “impeller”, it is necessary to fulfill the principles of the unity of the design and technological base in the process of the entire technological chain, including the assembly operation (figure 1).

![3D Model of "impeller" - type details as assembly.](image)

The main requirement to minimize the influence of the errors arising in the process of manufacturing individual elements (n-blades) on the assembly accuracy of the finished part $F_{\omega}$,

$$ F_{\omega} = \sum_{n=1}^{N} F_{n}^2 \equiv 0 \quad (1) $$

The problem is that typical manufacturing processes for such parts do not always meet these requirements.

In this paper, we consider the technological aspects of ensuring the accuracy of processing and assembly of the “impeller” part from the standpoint of comparing the components of the machining error and assembly arising from the implementation of traditional and hybrid technologies in relation to the “impeller” type parts.

In general, the objective function (1) of the process of ensuring the accuracy of the details of the “impeller” assembly can be:

$$ F_{t} = \sum_{i=1}^{N} F_{i}^2 (y_1, z_1, y_2, z_2, ..., y_n, z_n) \quad (2) $$
According to (2) the error \( F_t \), affecting the operation of the site (details) is the algebraic sum of the size manufacturing error \( Y \) - engineering base for machining \( n \) — grooves:

\[
\varepsilon_y = F(y_1, y_2, \ldots y_n),
\]

(3)
tool wear \( (y_1) \), depreciation tooling \( (y_2) \), external random factors (for example, change in part temperature, lack of coolant \( y_n \)), and size manufacturing errors \( Z \) - installation base for the assembly \( n \) — blades details:

\[
\varepsilon_x = F(z_1, z_2, \ldots z_n),
\]

(4)
tool wear \( (z_1) \), depreciation tooling \( (z_2) \), external random factors (for example, change in part temperature, lack of coolant \( z_n \)).

Let introduce the notation for each \( n \) — assembly member:

\[
D_n = \sum_{i=1}^{N} F_i^2(y_n, z_n)
\]

(5)
as a single set of error components \( F_t \).

When assembling the error data for each \( n \) — assembly elements are superimposed on each other, and an assembly error occurs \( F_s \). Due to the fact that the spatial position of each \( n \) — element of assembly in space is changed by the angle \( \lambda \), then the magnitude of the assembly error will be determined by the vector sum \( \overline{F_s} \) sets \( D_n \):

\[
\overline{F_s} = \sum_{i=1}^{N} \overline{D_n}
\]

(6)

where,

\[
\overline{D_n} = (\overline{y_1} + \overline{z_1}) + (\overline{y_2} + \overline{z_2}) + \cdots + (\overline{y_n} + \overline{z_n})
\]

(7)

Let for a unit sum of vectors \( (\overline{Y} + \overline{Z}) \) their coordinates are given \( (y_a, y_b, y_c, z_a, z_b, z_c) \) in rectangular coordinate system \((OABC)\). Then for (6), (7) we get:

\[
\overline{F_s} = \sum_{i=1}^{N} \overline{D_n} = \{y_a + z_a, y_b + z_b, y_c + z_c\}_1 + \{y_a + z_a, y_b + z_b, y_c + z_c\}_2 + \cdots + \{y_a + z_a, y_b + z_b, y_c + z_c\}_n
\]

(8)

Taking into account (3), (4), expression (1) will be reduced to the form:

\[
F_t = \sqrt{(y_1^2 + y_2^2 + \cdots + y_n^2)} + (z_1^2 + z_2^2 + \cdots + z_n^2)
\]

(9)

Given (8), expression (9) takes the form:

\[
F_t = \sqrt{(y_1^2 + y_2^2 + \cdots + y_n^2)} + (z_1^2 + z_2^2 + \cdots + z_n^2) +
\]

\[
+\sqrt{\left\{y_a + z_a, y_b + z_b, y_c + z_c\right\}_1 + \left\{y_a + z_a, y_b + z_b, y_c + z_c\right\}_2 + \cdots + \left\{y_a + z_a, y_b + z_b, y_c + z_c\right\}_n)^2}
\]

(10)

The expression (10) allows you to calculate the magnitude of the error in assembling each \( n \) — component assembly parts "impeller", taking into account the error of its processing. Expression (10) contradicts the objective function (1) and (2) to ensure the accuracy of the "impeller" part in terms of ensuring the accuracy of size processing \( Y \) - engineering base for machining \( n \) — grooves and size
manufacturing errors $Z$ - installation base for the assembly $n$ - blades details due to the need to take into account in the calculations $F_\omega$ vector magnitude of assembly error $F_s$. Consequently, in the calculations there is a contradiction in the form of inequality:

$$0 = F_\omega \neq \sum_{n=1}^{N} F_n^2 = \sum_{n=1}^{N} (F_t^2 + F_s^2)$$

(11)

For the case of processing dimensions $Y, Z$ of "impeller" - type details an AM cycle in the calculations (2),(3),(9) we can neglect the values of the components of the size errors $Y, Z$, due to the lack of machining, and in expressions (8), (10) the value $D_n$ as a set of error components $F_t$ due to their smallness (rotation of the workpiece by the angle $\lambda$ provides CNC machine). Then on an DMT processing cycle dimensions $Y, Z$ of "impeller" - type details based on the transformations of expressions (2), (3), (8), (9), (10), we have an equality close to true (1):

$$F_\omega \approx \sum_{n=1}^{N} F_t^2 = \sum_{n=1}^{N} (F_t^2 + F_s^2) \approx 0$$

(12)

According to (12), the use of DMT in building theological cycles of parts of the "impeller" - type will significantly reduce the impact of machining error on the accuracy of their manufacture, including by eliminating a number of superimposed errors of their assembly process. This provides additional stock to achieve a given manufacturing accuracy, as well as a resource for reducing process allowances for both one part and the metal intensity of the unit as a whole.

3. Practical significance

At present, such hybrid technological processes are increasingly finding their use in the production of parts of a wide range. The use of DMT allows you to control the properties of individual surfaces by combining various combinations of materials [15-17]. However, the parts obtained by this technology for the aviation industry are semi-finished products due to the need to re-install the parts on the machine for machining. This leads to errors of basing and installation. Therefore, at the present time, special technological complexes appear on the technological equipment market, allowing to realize hybrid technology on a full cycle on one machine.

Hybrid technological complexes based on 3-5 axial CNC machines [18–20] are used. This allows you to significantly increase the flexibility of the production chain without degrading the quality of products. An example of manufacturing parts of the type "impeller" on the proposed technology is illustrated in Figure 2.

![Figure 2. DMT-process of "impeller" - type details manufacturing.](image)

However, hybrid technological complexes are unique technological equipment, therefore they have a number of limitations. The greatest technical limit for such complexes is the limited working area set by the equipment manufacturer. A promising direction for the development of such hybrid technologies is the possibility of integrating technological heads for direct laser growing operations into existing CNC machines of enterprises [21]. This will ensure the implementation of the proposed hybrid technology with a direct link to the technological capabilities of the enterprise. The development of such systems will be described in the subsequent works of the authors.
References

[1] Overton G 2009 Laser additive manufacturing gains strength Laser Focus World 45 43-7
[2] Uhlmann E, Fleck C, Gerlitzky G and Faltin F 2007 Dynamical Fatigue Behavior of Additive Manufactured Products for a Fundamental Life cycle Approach Procedia CIRP 61 588-93
[3] Ngo T D, Kashani A, Imbalzano G, Nguyen K T Q and Hui D 2018 Additive manufacturing (3D printing): A review of materials, methods, applications and challenges Composites Part B: Engineering 143 172-96
[4] Ford S and Despesse M 2016 Additive manufacturing and sustainability: an exploratory study of the advantages and challenges Journal of Cleaner Production 137 1573-87
[5] Frazier W E 2014 Metal additive manufacturing: A review Journal of Materials Engineering and Performance 23 1917-28
[6] Westerweel B, Basten R J I and van Houtum G-J 2018 Traditional or Additive Manufacturing? Assessing Component Design Options through Lifecycle Cost Analysis European Journal of Operational Research 270 570-85
[7] Ali U, Mahmoodkhani Y, Imani Shahabad S, Vlasea M and Toyserkani E 2018 On the measurement of relative powder-bed compaction density in powder-bed additive manufacturing processes Materials and Design 155 495-501
[8] Yan Z, Liu W, Tang Z, Li M and Zhang H 2017 Review on thermal analysis in laser-based additive manufacturing Optics and Laser Technology 106 427-41
[9] Allevi G, Cibeca M, Fioretti R, Montanini R and Rossi G 2018 Qualification of additively manufactured aerospace brackets: A comparison between thermoelastic stress analysis and theoretical results Measurement: Journal of the International Measurement Confederation 126 252-8
[10] Yao Y, Huang Y, Chen B, Su Y and Feng J 2018 Influence of processing parameters and heat treatment on the mechanical properties of 18Ni300 manufactured by laser based directed energy deposition Optics and Laser Technology 105 171-9
[11] Harooni A, Iravani M, Khajepour A, Khalifa A and Gerlich A P 2018 Mechanical properties and microstructures in zirconium deposited by injected powder laser additive manufacturing Additive Manufacturing 22 537-47
[12] Spierings A B, Starr T L and Wegener K 2013 Fatigue performance of additive manufactured metallic parts Rapid Prototyping Journal 19 88-94
[13] Kumar M N, Venkatesh S and Hussain M M 2017 Experimental investigation on influence of process parameters in selective laser sintering on roundness using taguchi method Int. J. of Mechanical and Production Engineering Research and Development 7 45-52
[14] Bandyopadhyay A and Heer B 2018 Additive manufacturing of multi-material structures Materials Science and Engineering R: Reports 129 1-16
[15] Chae H M and Mazumder J 2010 Numerical modeling of direct metal deposition: Heat transfer / solute transport of ternary system Congress Proceedings 103 1330-5
[16] Je H and Suh J 2013 Software supports and E-manufacturing for DMT process Journal of Mechanical Science and Technology 27 2947-53
[17] Imran M K, Masood S H and Brandt M 2015 Direct Metal Deposition of H13 Tool Steel on Copper Alloy Substrate: Parametric Investigation Lasers in Manufacturing and Materials Processing 2 242-60
[18] Lorincz J 2014 Additive joins subtractive on advanced all-in-one machines: New levels of hybrid multifunction machines are here, as five-axis milling mixes with laser deposition welding technologies Manufacturing Engineering 152 67-77
[19] Lorincz J 2014 Game-changing technology on a roll Manufacturing Engineering 153 49-58
[20] Bax B, Rajput R, Kellet R and Reisacher M 2018 Systematic evaluation of process parameter maps for laser cladding and directed energy deposition *Additive Manufacturing* 21 487-94

[21] Ogin P A, Levashkin D G and Yaresko S I 2017 Block-Modular Principle of Build Composition Automatically Changeable Laser Modules for CNC Machines *Procedia Engineering* 206 1298-302