Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 111 (2022) 816–821

www.elsevier.com/locate/procedia

12th CIRP Conference on Photonic Technologies [LANE 2022], 4-8 September 2022, Fürth, Germany

Towards a universal manufacturing node: Requirements for a versatile, laser-based machine tool for highly adaptable manufacturing

Michael Jarwitz[a,*], David Traunecker[a], Christian von Arnim[b], Niklas Müller[c], Steffen Kramer[a,d]

[a]University of Stuttgart, Institut fuer Strahlwerkzeuge (IFSW), Pfaffenwaldring 43, 70569 Stuttgart, Germany
[b]University of Stuttgart, Institute for Control Engineering of Machine Tools and Manufacturing Units (ISW), Seidenstr. 36, 70174 Stuttgart, Germany
[c]University of Stuttgart, Institute for Machine Tools (IfW), Holzgartenstr. 17, 70174 Stuttgart, Germany
[d]Karlsruhe Institute of Technology (KIT), wbk Institute of Production Science, 76131 Karlsruhe, Germany

* Corresponding author. Tel.: +49-711-685-60209. *E-mail address:* michael.jarwitz@ifsw.uni-stuttgart.de

Abstract

The current trend in the context of Industry 4.0 towards small batch sizes and increasing product variety results in ever-changing requirements for both, the products and the production. This requires highly versatile, fully and easily adaptable, and efficient manufacturing environments that can meet these demands, ideally already on the level of the machine tool. Because of its versatility, the laser is a promising tool for such a machine tool, but there is still a considerable need for research in the field of system technology.

We consider the requirements for a versatile, laser-based machine tool for highly adaptable manufacturing, that utilizes the combination of laser-based manufacturing processes on one machine. The focus of the considerations lies on remote processes and the processing of metals. Five key research topics for the development of such a universal laser manufacturing node are identified: highly dynamic and precise kinematics (1); 'on-the-fly' reconfigurable, distributed control architectures (2); adaptable process diagnostics for online quality monitoring (3); technological interactions in laser-based process chains (4); and models for a fast estimation of the process parameters for each production step (5). The relevance and current needs for research for each topic are discussed and corresponding solution concepts are proposed.

Keywords: laser-based manufacturing; Industry 4.0; versatile machine tool; adaptable manufacturing; multi-process

1. Introduction

There is an ongoing trend towards increasing product variety and correspondingly decreasing batch sizes, while simultaneously aiming for a low price and short time-to-market. This can be observed in numerous manufacturing paradigms that evolved in the last decades, as e.g. mass personalization [1], Industry 4.0 [2], or more recently software-defined manufacturing (SDM) [3].

Consistently following this trend towards increasing product variety would lead to a scenario where every part to be manufactured is different (i.e. batch-size one). This would result in a case of ever-changing requirements for both, the products and the production, requiring manufacturing environments which are highly versatile, fully and easily adaptable, and efficient at the same time.

However, the versatility, adaptability, and efficiency must not only be fulfilled on the level of the manufacturing system, but rather directly on the level of the machine tool. Such a machine tool is for example considered one of the key enablers for SDM [4] and referred to as a 'universal manufacturing node' in [4].

In this context, high versatility means that a large set of different manufacturing processes must be accessible on one machine. The demand for easy adaptation means that the effort for the adaptation of the soft- and hardware must be minimized.

10.1016/j.procir.2022.08.090

This applies in particular to the hardware, since one major obstacle for the integration of a large set of different manufacturing processes on one machine has been identified to be the significant effort for the change of the involved hardware [5].

A very promising approach to overcome this obstacle is the combination of laser-based manufacturing processes, since the laser itself is already a versatile tool [5]. In principle, it is possible to cover all six main manufacturing groups of the German standard DIN 8580 using the laser as a common tool and only changing a few processing parameters [5]. This provides the opportunity to develop such a 'universal manufacturing node'. However, there is still a significant need for research in the field of system technology to actually realize this vision [5].

Therefore, we consider the requirements for such a versatile, laser-based machine tool for highly adaptable manufacturing, that utilizes the combination of laser-based manufacturing processes on one machine. It is assumed that the versatility of the laser can be exploited best when using remote processes, minimizing the need for additional hardware, such as auxiliary equipment for the supply of process gases or filler material. Therefore, the considerations focused mainly on remote (or remote-capable) processes. Furthermore, the considerations presented in this paper were made for the processing of metals, as a first step towards a universal laser manufacturing node. Under these boundary conditions, we identified five key research topics for the development towards such a universal laser manufacturing node:

- Kinematics: highly dynamic and precise kinematics are required to realize the different laser-based manufacturing processes on one machine and to utilize their full potential.
- Control architecture: an 'on-the-fly' reconfiguration of real-time applications and real-time networks is required to ensure a seamless switching between the different laser-based manufacturing processes.
- Adaptable process diagnostics: reliable online quality monitoring for different laser-based manufacturing processes and changing boundary conditions requires adaptable process diagnostics.
- Laser-based process chains: knowledge about the technological interactions in laser-based process chains is required to derive optimized production sequences.
- Parameter prediction models: models for the prediction of process parameters for the different laser-based manufacturing processes are required, minimizing time, material consumption, and experimental effort.

In the remainder of the paper, the relevance and current need for research for each topic are discussed and corresponding solution concepts are proposed.

2. Kinematics

The kinematics is a key element for the realization of manufacturing processes that require a relative movement between the tool and the workpiece. In the context of the universal laser manufacturing node where the laser is used as a tool, the main tasks of the kinematics are the movement and positioning of the laser beam and the adjustment of the laser beam diameter.

To ensure the versatility of the universal laser manufacturing node, the kinematics must offer the possibility to cover a large set of different manufacturing processes. For laser-based processes, this means that a large range of process parameters must be covered, ideally with no or only minimal adaptation of the involved hardware. An extensive literature review was performed to determine typical ranges for the process parameters for different laser processes. Specifically, the desired processing speeds range from 0.02 m/min up to an order of magnitude of 60 000 m/min, especially for processing with ultra-short laser pulses [6]. The laser beam diameter on the work piece should be adjustable in the range from about 10 µm to 12 mm. For the accuracy, a value in the single digit µm range has to be achieved at the tool center point. Further requirements are three-dimensional (3D) processing of components within a processing volume in the order of one or up to several m^3.

Current systems are limited in at least one of the following characteristics: the ability to 3D-machine large-volume components and to enable high dynamics while moving the laser beam. Systems for 3D processing of large-volume parts often originate from machine tools developed for mechanical machining processes. In these processes, high forces often act on the kinematics. Therefore, such kinematics systems are heavily mass loaded, which means the dynamics are limited. Systems with higher dynamics are restricted in the dimensionality or the working area. These are, for example, polygon scanners [7], which are used for particularly fast, but only one-dimensional processes. For two-dimensional dynamic processing of components, galvanometer scanners [8], piezoelectric galvanometer scanners [9] or electro-optical and acousto-optical scanners [10] are often used. However, these have a much smaller working area than the one aimed at with the universal laser manufacturing node. In addition, highly specialized kinematics are available, e.g. for the application of protective coatings [11] or for additive manufacturing [12] using extreme high-speed laser material deposition (EHLA).

Currently, no kinematics system is able to cover all requirements. Therefore, a novel design of the kinematics for laser-based manufacturing is required. This requires a holistic approach, including a systematic consideration of the fundamental principles and components for beam guidance, deflection, and focusing, as well as their integration into an overall kinematics concept. Especially, the moving mass must be minimized to achieve the high processing speeds aimed for. Focusing on remote processes, only the laser beam needs to be moved, and since the laser beam itself is massless, this should in principle be possible. The new design might include the following considerations. In case moving parts are still required, two of the promising actuators are electromagnetic or piezoelectric drives. These can, for example, drive a reflective element both rotationally and translatory. Angular ratios can be exploited advantageously for a high process velocity. This involves long propagation distances, which is why it is advisable to deflect the collimated laser beam. Also, changing the refractive properties of a deflecting element actively, for example via temperature or pressure, leads to the possibility of moving the laser beam at high velocities. An appropriate arrangement of the deflecting elements could ensure that 3D components can be produced. To ensure a dynamic adjustment of the laser beam diameter, one of the elements must allow for a change in its focusing properties, e.g. a deformable mirror.

3. Control

The control architecture is responsible for acquiring all sensor data and control all actuators of the universal manufacturing node in time. To achieve a consistently high process quality, a real-time control system is required. It must support switching between multiple laser-based processes on the fly, which includes exchanging real-time applications and reconfiguring the real-time network. To allow a continuous production, for example when switching from a continuous wave (CW) to an ultra-short pulse (USP) laser process, no restart of the manufacturing node must be required. Since different modules of the manufacturing node are active depending on the process currently being executed, a distributed control system patterned after a Cyber Physical Production Systems (CPPS) [13] architecture should be used instead of a single control system. Thereby, at each point in time, a specific set of control applications is running, which exchange different data with other control applications, sensors, and actuators using the real-time communication network. For this purpose, the real-time network also needs to be reconfigured, as e.g. for one specific process additional sensors might be evaluated, whereas for another manufacturing process additional axes might be controlled.

However, the possibilities for the reconfiguration of the universal laser manufacturing node are limited by the existing field bus networks. Some current field bus networks (e.g. Sercos III [14]) require to preallocate resources in the real-time network for all possible data that will be required by some manufacturing process. This is not desirable, as it might exceed the network capabilities and so the control applications would need to limit the exchanged data and cannot achieve the best possible result, as the real-time network is occupied by data, which is not required at that moment. Other field bus networks (e.g. Profinet IRT [15]) require a restart when additional data should be exchanged using a cyclic real-time communication.

To achieve a seamless reconfiguration of the real-time communication, the operations described in [16] should be implemented, which allow the reconfiguration of real-time networks without restarting the manufacturing node. These concepts utilize tolerances of real-time applications against a certain amount of jitter of the real-time communication to make multiple tiny adjustments to the real-time communication while maintaining the functionality of all control applications.

For each laser-based process of the universal laser manufacturing node, an individual set of control applications is required. For an uninterrupted switch of the laser-based processes, a reconfiguration of the real-time network without interrupting the communication is necessary to allow each laser-based process the exchange of data in the real-time network without the influence of past or future other laser-based processes of the manufacturing node. This shall be realized by combining the concept of a distributed CPPS control architecture with the previously described concept for the reconfiguration of the real-time network.

4. Adaptable process diagnostics for online quality monitoring

In today's manufacturing environment, quality, efficiency, and sustainability are more important than ever [17]. This requires a reliable quality monitoring system to detect defects as soon as possible, which ideally requires online monitoring [18]. A monitoring system for the universal laser manufacturing node is even more demanding, as various processes with different requirements for the quality monitoring have to be monitored. Therefore, the following aspects were considered particularly important for a reliable quality monitoring system:

- Adaptable to different laser processes and parts.
- Directly applicable from batch-size one onwards.
- Quality information must be gathered online.
- A lean setup that contains a small number of different sensors.

There has been a lot of research on the diagnostics of individual laser processes, see e.g. [19], which leads to the conclusion that non-invasive optical monitoring technologies are the ideal tool for in-process quality assurance [20]. The commonly used approach for the detection of defects is to correlate the measured data with the process parameters and the defects. This already works very well for the respective processes, but the major difficulty is to develop a system that can monitor several processes with a uniform sensor setup [21].

Therefore, the research is focused on the development of such an adaptable process monitoring system with a unique sensor setup. This requires multiple steps. At first, relevant defects and suitable measurands for their detection must be determined. Secondly, suitable sensors for the measurands have to be identified, and thirdly, suitable data processing methods must be developed for reliable online detection of the defects.

An extensive literature review showed that, in general, the identified defects can be approximately divided into surface defects, such as excess weld metal, and internal defects, such as pores. Surface defects can be detected directly with a length measurement within a two-dimensional (2D) measurement area. A scanning optical coherence tomography (OCT) system could be suitable as a sensor which has already been shown in [22]. Internal defects can only be measured directly online with great effort, e.g. pores with an integrated X-ray diagnostic. Therefore, indirect measurements are required in this case, with a 2D temperature measurement being one promising measurand. The disadvantage with indirect measurements is that reference values are necessary for the detection of the defects. For this reason, more research is needed compared to the detection of the surface defects, which also includes the selection of a suitable sensor. Two different sensors were determined for the 2D temperature measurement, a thermographic camera and a pyrometer combined with a galvo scan head to move the pyrometer spot. Which one is best suited for the detection of internal defects will be further investigated.

As already mentioned, suitable data processing methods are essential for a reliable online monitoring system. Different evaluation methods are suitable for different laser processes [21]. Therefore, the data processing methods must also be adapted to the processes. Advanced evaluation methods such as machine learning and statistical techniques could be suitable for this. In particular, the combination of different methods is a promising approach for quality control [23] and promising for the use in a universal laser manufacturing node. Further investigations are required to develop and select appropriate methods.

5. Laser-based process chains

From the perspective of manufacturing technology, a universal laser manufacturing node enables the realization of versatile and adaptable process chains consisting of a variety of process combinations. From process chains using mainly conventional manufacturing processes like casting, forming, milling, or turning, it is known that technological interactions between processes need to be considered to derive an optimized process chain to achieve the desired part properties [24].

The laser as a manufacturing tool differs significantly from conventional manufacturing tools in such a way that it works contactless and with high energy concentrations, which are applied locally [25]. Because of the differences in the interactions between the tool and the material, the knowledge about the technological interactions from conventional process chains cannot be applied directly to laser-based process chains. Therefore, the resulting technological interactions between laser-based manufacturing processes need to be investigated.

Technological interactions are hereby defined as the functional relationships between the initial state and the final state of the part, before and after the various processes, concerning part properties such as density, microstructure, surface quality, or deformation and the impact of these relationships on the process chain itself.

To ensure that a part produced purely by a laser-based process chain has satisfactory mechanical and physical properties, three main points need to be addressed:

- Acquiring extensive knowledge about technological interactions between combinations of two individual laser-based processes.
- Extension of the observed technological interactions to process chains comprising more than two consecutive laser-based processes.
- Providing the collected knowledge in an accessible digital form which supports the derivation of laser-based process chains for specific parts.

Whereas common individual laser processes like laser welding, laser cutting, selective laser melting (SLM), or laser ablation with ultra-short laser pulses are well investigated, combinations of laser-based manufacturing processes are only starting to attract attention. Research activities mainly focus on the following combinations:

- Laser welding of SLM-produced parts [26] including comparisons with other welding processes [27] or with conventionally produced parts [28].
- Surface modification and post-processing using multiple laser processes, e.g. laser ablation and laser polishing [29], or laser heat treatment [30].
- Combination of laser cutting and laser welding with the same processing head [31].

An extensive literature research showed, that combinations of more than two laser processes or entire laser-based process chains have not yet been investigated thoroughly. Therefore, knowledge for distinct process combinations and especially for entire process chains must be extended. Processes which will be considered for possible process chains include SLM, laser welding, laser ablation, and laser heat treatment, as these are expected to enable a wide range of industrial relevant process combinations and process chains.

A digital tool will be built to make the findings accessible, so the investigated technological interactions can be used to design and optimize laser-based process chains. This can be achieved by a standardized description of process properties and interfaces between different laser-based processes [32].

The potentials and limitations of laser-based process chains concerning part properties, process times, and economic efficiency will be evaluated, taking conventional process chains as a benchmark.

In the future, this concept could also be extended to include parallel processes, extending the potentials of laser-based process chains even further [33].

6. Parameter prediction models

Since every part to be manufactured might be different (batch-size one), also the optimum process parameters for a new part are not necessarily known a priori but must be determined anew each time. To ensure the adaptability and efficiency of the universal laser manufacturing node, the determination of the process parameters must ideally be carried out fast (i.e. in a short time) and with minimal effort (experimental and material), and should also be applicable for a wide range of boundary conditions.

A model-based procedure should be used to predict the process parameters in order to minimize the experimental effort. Existing models of laser-based manufacturing processes include physics-based models, ranging from simple analytical models, e.g. describing the resulting temperature distribution in a laser-heated sample [34], to complex multi-physical models, see e.g. [35], as well as data-based models, such as machine learning (ML), e.g. [36]. These models usually provide a prediction of the processing results for a given set of process parameters. Finding optimized process parameters, however, requires the inverse problem to be solved (i.e. predicting the process parameters for a given set of process results), which usually has many possible solutions and therefore requires an iterative procedure. The different types of models of laser-based processes all have some advantages and disadvantages. For example, analytical models typically have very short calculation times (in the order of seconds or below), but are often restricted to specific boundary conditions, while some multi-physical numerical models can describe the process results quite accurately, see e.g. [35], at the cost of long calculation times (which can be up to weeks or even months [35]). ML models have the advantage that they can model even complex nonlinear relationships without the need of an explicit description of all involved phenomena [36], but this often requires a huge amount of training data [36] which can significantly increase the experimental effort. Moreover, ML models are often bad at extrapolation [37], which can limit their applicability to new parts. It is also worth noting, that solving an inverse problem directly with an ML model is usually not practical because ML models generally do not perform well when there are many possible solutions [37].

Therefore, the proposed approach is to use a combination of physics- and data-based models (also known as hybrid modeling [38]) to leverage the advantages of both types of models to allow for a fast prediction of the process parameters for a wide range of process and boundary conditions. Possible approaches for the development of such hybrid models could comprise the following. ML models could be used as surrogate models for more complex and computational intensive physics-based models [37] to reduce the calculation times. Also, the accuracy of fast but simplified physics-based models could be improved through modeling the deviation to the actual process results using an ML model (a so-called "parallel approach" [38]). Another possible approach is to integrate physical knowledge directly into an ML model, by incorporating it into the loss function of the ML model (as e.g. in 'physics-informed neural networks' [39]), to extend the applicability of the model and ensure its consistency with the laws of physics.

The investigation and evaluation of the different approaches and their combinations for the prediction of process parameters will be the subject of future work.

7. Conclusion

Even though the laser itself is already a quite versatile tool, for the development of a universal laser manufacturing node there is still a significant amount of research required in different topics. Under the considered boundary conditions, research needs were identified for five key research topics and corresponding solution concepts proposed. In the future, the main research focus in these research topics will be:

- The development of a novel design of the kinematics for laser-based manufacturing.
- The combination of a distributed CPPS control architecture with a concept for 'on-the-fly' reconfiguration of real-time networks.
- Investigation of suitable sensors and data processing methods for an adaptable and reliable online quality monitoring system.
- Investigation of the technological interactions in laser-based process chains and the development of a digital tool to make the findings accessible.
- Investigation of different approaches for the development of hybrid models for a fast prediction of process parameters.

The future progress and results in these research topics will represent a first step towards a universal laser manufacturing node and contribute to its development. Realizing the vision of a universal laser manufacturing node will probably involve even more research topics than those discussed in this paper. Even though the focus on remote processes minimizes the needed auxiliary equipment, still some auxiliary equipment will probably be needed, e.g. for the extraction of process emissions, such as fume or metal vapor, from the process zone. The further development of such auxiliary equipment might be one of those further research topics. Also, extending the range of materials that can be processed to include not only metals but a wide range of different materials will probably increase the requirements imposed on the machine.

Acknowledgements

The presented work was funded by the Ministry of Science, Research and the Arts of the Federal State of Baden-Wuerttemberg within the "InnovationCampus Future Mobility", which is gratefully acknowledged.

References

[1] Hu SJ. Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization. Procedia CIRP 2013;7:3-8.
[2] Cohen Y, Faccio M, Pilati F, Yao X. Design and management of digital manufacturing and assembly systems in the Industry 4.0 era. Int J Adv Manuf Technol 2019;105(9):3565-3577.
[3] Lechler A, Verl A. Software Defined Manufacturing extends cloud-based control. In: Proceedings of the ASME 2017 12th MSEC2017.
[4] Xu L, Chen L, Gao Z, Moya H, Shi W. Reshaping the Landscape of the Future: Software-Defined Manufacturing. Computer 2021;54(7):27-36.
[5] Graf T, Hoßfeld M, Onuseit V. A Universal Machine: Enabling Digital Manufacturing with Laser Technology. In: Heieck F, Ackermann C, editors. Advances in Automotive Production Technology - Theory and Application. ARENA2036. Berlin, Heidelberg: Springer Vieweg; 2021. p. 386-393.
[6] Weber R, Graf T, Freitag C, Feuer A, Kononenko T, Konov VI. Processing constraints resulting from heat accumulation during pulsed and repetitive laser materials processing. Optics express 2017;25(4):3966–3979. doi: 10.1364/OE.25.003966.
[7] Loeschner U, et al. High-rate laser microprocessing using a polygon scanner system. J Laser Appl 2015;27:S29303. doi: 10.2351/1.4906473.
[8] Maruyama S, et al. Pulsed laser deposition with rapid beam deflection by a galvanometer mirror scanner. Rev Sci Instrum 2019;90(9):93901. doi: 10.1063/1.5104291.
[9] Chiu YC, Lin CY, Yen CY, Huang YH. Development of a new piezoelectric galvanometer scanner: fabrication, operation, and measurements. Smart Mater Struct 2021;30(7):74001. doi: 10.1088/1361-665X/ac028e.
[10] Heberle J, Bechtold P, Strauß J, Schmidt M. Electro-optic and acousto-optic laser beam scanners. SPIE LASE, San Francisco, California, United States, 2016, 97360L, doi: 10.1117/12.2212208.
[11] Schopphoven T, Gasser A, Backes G. EHLA: Extreme High-Speed Laser Material Deposition. LTJ 2017;14(4):26–29. doi: 10.1002/latj.201700020.
[12] Schopphoven T, Schleifenbaum JH, Tharmakulasingam S, Schulte O. Setting Sights on a 3D Process. PhotonicsViews 2019;16(5):64–68. doi: 10.1002/phvs.201900041.
[13] Cruz Salazar LA, Ryashentseva D, Lüder A, Vogel-Heuser B. Cyber-physical production systems architecture based on multi-agent's design pattern—comparison of selected approaches mapping four agent patterns. Int J Adv Manuf Technol 2019;105(9):4005–4034. DOI: 10.1007/s00170-019-03800-4.

[14] Neumann P. Communication in industrial automation—What is going on? Control Engineering Practice 2007:15(11):1332–1347. DOI: 10.1016/j.conengprac.2006.10.004.
[15] Dürkop L, Jasperneite J, Fay A. An analysis of real-time ethernets with regard to their automatic configuration. In: 2015 IEEE World Conference on Factory Communication Systems (WFCS). IEEE, 2015.
[16] von Arnim C, Lechler A, Riedel O. Operations for non-disruptive modification of real-time network schedules. In: 2021 22nd IEEE International Conference on Industrial Technology (ICIT).
[17] Stavropoulos P, Chantzis D, Doukas C, Papacharalampopoulos A, Chryssolouris G. Monitoring and control of manufacturing processes: A review. Procedia CIRP 2013;8:421–425. doi:10.1016/j.procir.2013.06.127.
[18] Thombansen U, et al. Design framework for model-based self-optimizing manufacturing systems. Int J Adv Manuf Technol 2018;97:519–528. doi: 10.1007/s00170-018-1951-8
[19] Purtonen T, Kalliosaari A, Salminen A. Monitoring and adaptive control of laser processes. Physics Procedia 2014;56:1218–1231. doi: 10.1016/j.phpro.2014.08.038.
[20] Stavridis J, Papacharalampopoulos A, Stavropoulos P. Quality assessment in laser welding: a critical review. Int J Adv Manuf Technol 2018;94:1825–1847. doi: 10.1007/s00170-017-0461-4.
[21] Vaamonde E, Panadeiro V, Gonzalez C, Arias JL. On-Line Quality Monitoring System for Multi-Functional Laser-Based Processing Based on Embedded VIS and MWIR Computer Vision. Proceedings of ICALEO 2019;1304.
[22] Dupriez ND, Denkl A. Advances of OCT Technology for Laser Beam Processing. LTJ 2017;14(4):34–38. doi: 10.1002/latj.201700021.
[23] Le-Quang T, et al.. Why is in situ quality control of laser keyhole welding a real challenge? Procedia CIRP 2018;74:649–653. doi: 10.1016/j.procir.2018.08.055.
[24] Denkena B, Henjes J, Henning H. Simulation-based dimensioning of manufacturing process chains. CIRP Journal of Manufacturing Science and Technology 2011;4:9-14. doi: 10.1016/j.cirpj.2011.06.015
[25] Hügel H, Graf T. Laser in der Fertigung – Strahlquellen, Systeme, Fertigungsverfahren. 2nd ed. Wiesbaden: Vieweg + Teubner; 2009.
[26] Mäkikangas J, Rautio T, Mustakangas A, Mäntyjärvi K. Laser welding of AlSi10Mg aluminium-based alloy produced by Selective Laser Melting (SLM). Procedia Manufacturing 2019;36:88-94. doi: 10.1016/j.promfg.2019.08.013
[27] Zhang C, Bao Y, Zhu H, Nie X, Zhang W, Zhang S, Zeng X. A comparison between laser and TIG welding of selective laser melted AlSi10Mg. Optics and Laser Technology 2019;120:105696. doi: 10.1016/j.optlastec.2019.105696
[28] Möller B, Schnabel K, Wagener R, Kaufmann H, Melz T. Fatigue assessment of additively manufactured AlSi10Mg laser beam welded to rolled EN AW-6082-T6 sheet metal. Int J of Fatigue 2020;140:105805. doi: 10.1016/j.ijfatigue.2020.105805
[29] Solheid JS, Wunsch T, Trouillet V, Weigel S, Scharnweber T, Seifert HJ, Pfleging W. Two-step laser post-processing for the surface functionalization of additively manufactured Ti-6Al-4V parts. MDPI Materials 2020;13:4872. doi: 10.3390/ma13214872
[30] Rautio T, Mäkikangas J, Mustakangas A, Mäntyjärvi K. Disk laser assisted surface heat treatments of AlSi10Mg parts produced by selective laser melting (SLM). Proc Manuf 2019;36:95-100. doi: 10.1016/j.promfg.2019.08.014
[31] Petring D, Schneider F, Dickler H. Progress in cutting and welding of sheet metal assemblies in one machine with the laser combi-head. PICALO 2010;1001. doi: 10.2351/1.5057171
[32] Bettin V. Ansatz zur übergreifenden Qualitätsregelung von Prozessketten in der Fertigung, Diss. Berichte aus dem Lehrstuhl Qualitätsmanagement und Fertigungsmesstechnik, Friedrich-Alexander-Universität Erlangen Nürnberg Bd. 9, 2003.
[33] Henn M, Buser M, Onuseit V, Weber R, Graf T. Combining LPBF and ultrafast laser processing to produce parts with deep microstructures. In: Proceedings of the Lasers in Manufacturing Conference 2021.
[34] Cline HE, Anthony TR. Heat treating and melting material with a scanning laser or electron beam. J Appl Phys 1977;48(9):3895-3900.
[35] Dal M, Fabbro R. [INVITED] An overview of the state of art in laser welding simulation. Optics & Laser Technology 2016;78:2-14.
[36] Mills B, Grant-Jacob JA. Lasers that learn: The interface of laser machining and machine learning. IET Optoelectronics 2021;15(5):207-224. DOI: 10.1049/ote2.12039
[37] Gauger I, Nagel T, Huber M. Hybrides Maschinelles Lernen im Kontext der Produktion. In: Hartmann EA, editor. Digitalisierung souverän gestalten II. Berlin, Heidelberg: Springer Vieweg; 2022. p. 64-79.
[38] Sohlberg B, Jacobsen EW. Grey box modelling - branches and experiences. In: IFAC Proceedings 2008;41(2):11415-11420.
[39] Raissi M, Yazdani A, Karniadakis GE. Hidden fluid mechanics: learning velocity and pressure fields from flow visualizations. Science 2020;367:1026-1030.