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Review on the Use of Machine Learning Techniques to Optimize the Processing of Copper Alloys in Additive Manufacturing

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Additive manufacturing is a popular research and development direction that has received much attention from academia and industry in recent years.Thanks to significant advances in laser and other related technologies over the last decade, laser powder bed fusion (L-PBF)has shown potential for specific applications in a variety of metals. At the same time, the development and upgrading of high-strength copper alloys have been a hot topic of research and development in the traditional metals industry as industrial production chains around the world have become increasingly concerned with environmental issues.Hence,combining these two directions and using machine learning to rapidly optimize the processing of copper alloys by L-PBF is a clear and practically relevant research direction.

NOMENCLATURE

ML=machine learning
E=Energy of the laser
h=De Broglie's constant
c=Speed of light
λ =Wavelength of the laser

1. Introduction

1.1 Laser-based powder bed fusion for metals

Laser-based powder bed fusion(L-PBF) technology heats metal powder by employing a laser heat source and melts the metal powder layer by layer by following a designed model to form a small volume of the molten pools, which subsequently solidify rapidly to form high-strength metal structural parts with a complex three-dimensional (3D) structure[2].At the same time, structural metal parts produced using L-PBF technology do not need to be machined in-depth[2] and can be put into service quickly, so L-PBF technology offers significant advantages in terms of reduced machining time and increased precision.L-PBF technology has been used forvarious alloys such as iron, nickel and titanium-based alloys and is becoming increasingly mature[2].

This technology is limited by the power of the laser source and the development of fiber optic technology, so the processingofcopper alloys using L-PBF is relatively late as compared to other alloys[1].

1.2The principle of using machine learning to optimize new copper alloys

For metallic materials suitable for additive manufacturing (AM), there are many factors that affect material suitability. In certain circumstances, different 3D printer models or different product structures have different requirements for raw materials. In this process, the composition of traditional copper alloys requires secondary optimization to obtain better-performing printed products.Therefore, trying to transform this problem into an optimization problem and trying to solve it with the help of machine learning combined with appropriate algorithmic strategies will accomplish the goal much faster.

Experience from successful experiments[3,4] has shown that the proven approach is to first determine the original hyperparameters through a screening process and subsequently use Bayesian optimization to solve the problem. The reason why Bayesian optimization is commonly used is that by using this method, the optimal values of the independent variables and their corresponding dependent variables can be eventually obtained by guessing, without being sure of the exact form of the functionand faster than other methods.

2. Additive manufacturing of copper alloys

2.1 Laser powder bed fusion for copper alloys

As copper alloys have important applications in all areas of human society, the processingof copper alloys usingAM technology is an inevitable trend.

With the development of the times and the further increase in the performance requirements of the corresponding products, the processing difficulties for copper alloy products are also increasing.The advantages of L-PBF technology, such as rapid prototyping, low manufacturing costs and complex structures, are becoming more and more important and have therefore attracted extensive academic attention in recent years[5].However, current research is relatively limited for copper alloys and the combination with L-PBF technology is still in the exploratory stage. There are needs for these materials to be tested with specific designs of copper alloys under specific printing parameters[6].

2.2Challenges and potential for processing copper using L-PBF

For copper alloys, the current limited maturity in L-PBF technology compared to other alloys such as titanium is due to the better thermal conductivity of copper alloys and their higher reflectivity for lasers. This also means that copper alloys in their powder form do not melt easily.It is therefore necessary to increase the absorption rate of the laser by increasing the laser power or by recoating the copper alloy powder with a coating[6,7].The method of increasing the laser power is to shorten the wavelength of the laser, based on the principle of Equation 1

$$E = \frac{hc}{\lambda} \quad (1)$$

The better picture, however, is that the current exploration in both directions is yielding good results. Whether by reducing the laser wavelength or by applying a new coating to the powder, the laser absorption of copper alloy powders has been significantly improved.In the future, therefore, by further reducing the laser wavelength or designing new coatings, it is expected that the upper-performance limit of copper alloys in AM can be increased to meet more complex structures or performance requirements.

3. Future research direction

3.1 New alloy composition designs

CuCrZr, as a copper alloy specifically designed for L-PBF technology, has yet to be tested for its ability to adapt to the different requirements of a wide range of copper alloys and therefore needs to be re-optimized for special high-performance requirements in areas such as nautical exploration, aerospace, high-speed rail power delivery, etc.

For example, new research suggests that copper-containing titanium alloys may have potential applications in the biomedical field[8]. Byusing AM techniques for processing, their content ratios of different elements can be adjusted which will allow the fabrication of complex structures while providingsuitable healing and biocompatibility in the medical field.Similarly, further improvements in the electrical conductivity of additively manufactured copper alloys have been made. It has been shown that porosity has an influence on conductivity and therefore the addition of zinc to pure copper may improve this application index[9].

More research is needed to realize the great potential for adapting the composition of copper alloys to meet specific performance targets while adapting to L-PBF processing methods.

3.2 In-situ alloying

In-situ alloying has been used in alloys such as titanium-tantalum[10], aluminium-copper[11] and copper-silver alloys[12], but copper-based alloys still face the effects of high thermal conductivity as well as laser reflection in the alloying process.

At the same time, there is still a lack of consideration and optimization of whether the new alloy after *in-situ* alloying will be able to exploit the effect of each added element in the alloy or a specific property of the alloy, as well as the overall manufacturing cost. For example, it is unclear whether copper-silver alloys prepared by *in-situ* alloying are biocompatible or antibacterial, and there is a lack of adjustment of the corresponding preparation parameters when using the corresponding alloys.Relatively little has been reported on other potential new copper alloys or *in-situ* alloying of complex copper alloys. Due to the long history of copper alloy applications, the preparation of complex copper alloys is a promising and relevant research direction.

3.3 Integration of machine learning

The application of machine learning(ML) is, in the authors' opinion, based on the need to design new alloy compositions and the optimization of preparation parameters in the *in-situ* alloying process.

For high-strength copper alloys, there has been a history of using ML for composition design[13], with the procedure flowing as shown in Figure 1.

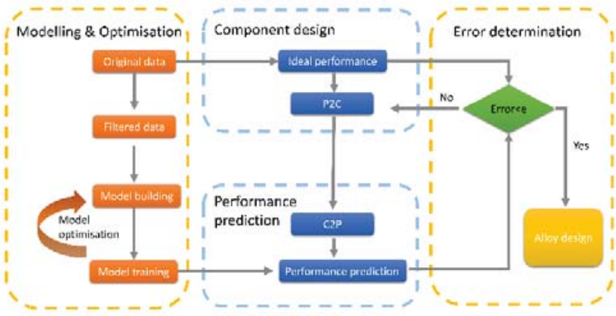

Fig. 1Schematic diagram of the workflow of anML program for the design of high-strength copper alloy compositions[13,14]

However, this process only addresses the requirements for tensile strength and electrical conductivity of copper alloys, but less attention has been paid to other aspects of copper alloy properties, or to secondary optimization of the properties of existing copper alloys.Similarly, once the composition of the copper alloy has been determined, the process parameters need to be adjusted again to meet the commercial value and the optimum solution for the specific properties of the alloy. This process can still be done with the help of ML, where the answer is found by solving an optimization problem after several key parameters have been selected.

Alternatively, it is possible to consider establishing a link between the product properties, the alloy composition and the process parameters at the same time and to obtain the optimum composition design and its corresponding process parameters in a single step by means of a functional relationship. However, this idea is more complex and difficult to solve, and there is currently almost a gap in academic exploration.In the coming years, as computing power and ML technology develop again, it may be possible to achieve this vision through new optimization models or time reductions brought about by increased computing power.

CONCLUSION

As we can see from the above discussion, the technical barriers have now been breached for the manufacture of copper alloys in L-PBF technology and are therefore technically achievable. However, due to the inherent characteristics of copper alloys and the complex composition of current special copper alloys, it will still take time to achieve a full replacement of traditional metallurgical manufacturing methods.The main difficulty lies in the melting of copper alloys. There are two major R&D directions for this step, among which the need to introduce ML technology for the optimized design of copper alloy compositions can be considered to simplify the R&D process and shorten the R&D time, while the establishment and optimization of new models still requires further efforts from a new generation of researchers.

In the case of copper alloys, the existing market and its potential remainhuge, while L-PBF technology can accordingly address the need for complex structures and rapid prototyping. Combining these two technologies is a direction with clear application prospects and value and promises to be a revolution for the industry in the future.

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REFERENCES

1. Yap CY, Chua CK, Dong ZL, Liu ZH, Zhang DQ, Loh LE, Sing SL. Review of selective laser melting: Materials and applications. Applied physics reviews. 2015 Dec 9;2(4):04110
2. Xiaoye Cai, Tong Liu, Xuan Yan, Zonghui Cheng, Lu Pan, Zongjun Tian, Liangshun Luo, Yanqing Su,Effect of process parameters on microstructures and properties of Al–42Si alloy fabricated by selective laser melting,Heliyon,Volume 8, Issue 6,2022,e09680,ISSN 2405-8440
3. Hongtao Zhang, Huadong Fu, Shuaicheng Zhu, Wei Yong, Jianxin Xie,Machine learning assisted composition effective design for precipitation strengthened copper alloys,Acta Materialia,Volume 215,2021,117118,ISSN 1359-6454
4. Seobin Park, Saif Haider Kayani, Kwangjun Euh, Eunhyeok Seo, Hayeol Kim, Sangeun Park, Bishnu Nand Yadav, Seong Jin Park, Hyokyung Sung, I'm Doo Jung,High strength aluminium alloys design via explainable artificial intelligence,Journal of Alloys and Compounds,Volume 903,2022,163828,ISSN 0925-8388
5. Z. Ma, D.Z. Zhang, F. Liu, J. Jiang, M. Zhao, T. Zhang, Lattice structures of Cu-Cr-Zr copper alloy by selective laser melting: microstructures, mechanical properties and energy absorption, Mater. Des., 187 (2020)
6. Xiangpeng Tang, Xiaohong Chen, Fujia Sun, Lei Li, Ping Liu, Honglei Zhou, Shaoli Fu, Allen Li,A study on the mechanical and electrical properties of high-strength CuCrZr alloy fabricated using laser powder bed fusion,Journal of Alloys and Compounds,Volume 924,2022,166627,ISSN 0925-8388
7. P. Lassègue, C. Salvan, E. De Vito, R. Soulas, M. Herbin, A. Hemberg, T. Godfroid, T. Baffie, G. Roux,Laser powder bed fusion (L-PBF) of Cu and CuCrZr parts: Influence of an absorptive physical vapor deposition (PVD) coating on the printing process,Additive Manufacturing,Volume 39,2021,101888,ISSN 2214-8604
8. Yanxi Li, Yanjin Lu, Bingrun Qiu, Yiting Ze, Peiran Li, Yu Du, Ping Gong, Jinxin Lin, Yang Yao,Copper-containing titanium alloys promote angiogenesis in irradiated bone through releasing copper ions and regulating immune microenvironment,Biomaterials Advances,Volume 139,2022,213010,ISSN 2772-9508
9. Diego Corona, Oliviero Giannini, Stefano Guarino, Gennaro Salvatore Ponticelli, Mariano Zarcone,Experimental investigation on the electrical, thermal, and mechanical properties of laser powder bed fused copper alloys,Journal of Manufacturing Processes,Volume 76,2022,Pages 320-334,ISSN 1526-6125
10. S. Huang, S.L. Sing, G. de Looze, R. Wilson, W.Y. Yeong Laser powder bed fusion of titanium-tantalum alloys: compositions and designs for biomedical applications J. Mech. Behav. Biomed. Mater., 108 (2020), p. 103775
11. R. Martinez, I. Todd, K. Mumtaz, In situ alloying of elemental Al-Cu12 feedstock using selective laser melting, Virtual Phys. Prototyp., 14 (2019), pp. 242-252
12. John Robinson, Arun Arjunan, Mark Stanford, Iain Lyall, Craig Williams,Effect of silver addition in copper-silver alloys fabricated by laser powder bed fusion in situ alloying,Journal of Alloys and Compounds,Volume 857,2021,157561,ISSN 0925-8388
13. C. Wang, H. Fu, L. Jiang, D. Xue, J. Xie, A property-oriented design strategy for high performance copper alloys via machine learning, NPJ Comput. Mater., 5 (2019), pp. 57-64
14. Xiujuan Liu, Pengcheng Xu, Juanjuan Zhao, Wencong Lu, Minjie Li, Gang Wang,Material machine learning for alloys: Applications, challenges and perspectives,Journal of Alloys and Compounds,Volume 921,2022,165984,ISSN 0925-8388