Chapter 4

Manufacturing of Ceramic Materials With 3D Selective Laser Melting and Analysis of Their Possible Applications for Ballistic Purposes

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Abstract

Selective laser melting (SLM) or selective laser sintering (SLS) methods are part of additive manufacturing techniques that involve work on a wide range of materials, including ceramic materials. Moreover, SLM is known to be able to produce customized components of various materials such as metal, ceramics and polymers and hence is a popular manufacturing method. Studies emphasize that these techniques also have potential for analysis of possible applications for ballistic purposes. Just as there are studies examining the mechanical properties of ceramic materials produced by the selective laser melting method, there are also studies on the marginal compatibility of ceramics used in the creation of ceramic plates.

The development of advanced ceramic materials for ballistic applications has been a topic of interest in the defense industry. Metals, ceramics and composite materials are generally used in personnel and vehicle armor applications. However, today, composite or hybrid composite designs come to the fore as a result of evaluating the level of protection together with the weight parameter. When the literature is examined; It shows that additive manufacturing techniques can also be used in the production of ceramic materials and therefore are preferred in armor production. In the study where the literature is examined in detail, it is emphasized that the most popular materials of ceramics in recent years are alumina and zirconia, which are among the main engineering material groups. Al2O3 is widely used as ceramic material in various industrial sectors, exhibiting high strength, hardness and excellent dielectric properties. On the other hand, ZrO2 is often added to increase the toughness and wear resistance properties of

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ceramic composites, making it a valuable addition to ceramic formulations. The combination of Al2O3 and ZrO2 has demonstrated promising results in improving the mechanical and ballistic properties of functionally graded materials, increasing fracture resistance and wear properties. In this study, a general evaluation of the studies in the existing literature is presented on the production of ceramic materials by 3D Selective Laser Melting and the analysis of their possible applications for ballistic purposes.

1. Introduction

Ceramic materials are an important class of materials for ballistic protection applications in the defense industry due to their properties such as high temperature resistance, high hardness, high strength and low density. It has advantages such as relatively high mechanical and tribological properties, high specific strength and hardness. Reinforced composites have many advantages such as low density and high strength. However, the fiber could not be used independently due to low impact resistance and high cost. For this reason, applications such as strengthening composite hybrid laminated plates including ceramic plates, including intermediate layers, considering that they disrupt the piercing structure of the threat by absorbing the kinetic energy of the threat, are promising. The limitations of ceramic materials obtained by traditional production methods encourage the use of 3D printing technologies in the production of ceramic materials. In this context, the production of ceramic materials, especially Al2O3 (alumina) and ZrO2 (zirconia), by selective laser melting 3D printing method is of great importance to evaluate potential applications for ballistic purposes.

3D printing, also known as additive manufacturing, is a shaping method in which a 3D computer model is sliced into 2D sections to create a physical structure through the addition of material layer by layer. Within this general definition, there are many specific technologies that vary in raw material and forming/bonding method for specific materials and applications. This differs significantly from more traditional subtractive or equivalent manufacturing methods that have been used for hundreds of years and allows the fabrication of structures that would otherwise be impossible to create relatively quickly and efficiently. This has allowed different industries to create exciting new parts and products, while saving time and money and improving performance [1-5]. However, the main materials used for 3D printing so far are polymers and metals; Ceramics, on the other hand, are relatively less researched and developed. However, in recent years, there has been a significant increase in the interest and use of ceramic materials due to the many useful application areas of ceramic materials as well as 3D printing technologies. Characterized by excellent thermal, chemical and electrical durability and stability, high strength and hardness, and useful optical properties, ceramics are ideal materials for applications in aerospace, medical, military and defense, electronics and many other industries [6-8].

In recent years, the production of ceramic materials with 3D printing technologies has been developing rapidly. These technologies offer many advantages compared to traditional methods in the production of ceramic materials. In particular, the selective laser melting 3D printing method provides high precision in the production of ceramic materials, production of high-density parts, production of complex geometries and material savings. Therefore, the selective laser melting 3D printing method has significant potential in the production of ceramic materials for ballistic protection applications.

Selective laser melting (SLM) is a powder bed-based layer manufacturing technique that enables additive manufacturing of complex-shaped objects directly from 3D CAD data. SLM is based on the direct and complete melting of powder material with a laser beam. SLM for metallic materials is already used successfully in industry. A comparable additive manufacturing technique is not yet available for high-performance ceramic materials such as zirconia or alumina. For less challenging materials containing silica or glassy phases, there are laser-based additive manufacturing approaches and solid-state sintering-based approaches described in the literature [9].

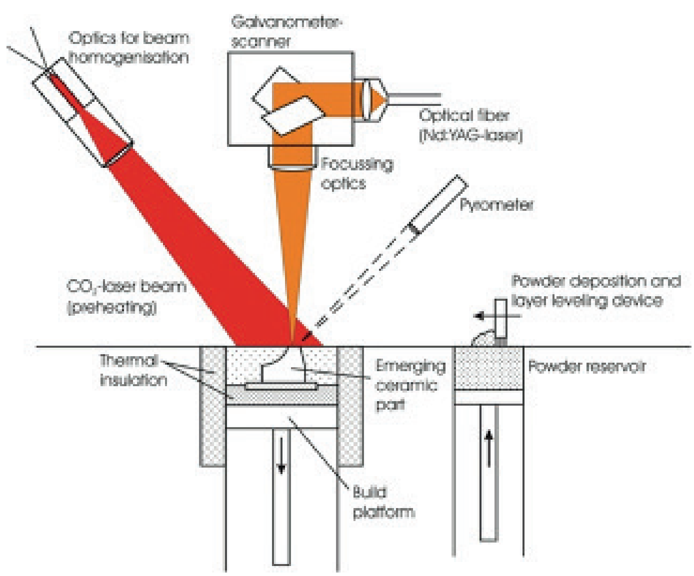

Figure 1. Schematic illustration of the experimental SLM system [10].

The SLM creation process consists of four main steps [10]: A thin layer of ceramic powder material is deposited on the build platform. Appropriate areas of the powder layer are selectively heated and melted by means of a focused laser beam. The building platform is lowered by a distance corresponding to the layer thickness. Steps are repeated until all layers are created (Figures 1,2 and 3).

Studies in this field include many researches on the production of ceramic materials by selective laser melting 3D printing method. For example, Wilkes et al. [10], a selective laser melting 3D printing method was developed for the production of high-strength oxide ceramics. Selective laser melting of a 1600°C preheated Zirconia and alumina ceramic materials was experimentally investigated. To reduce thermally induced stresses, the ceramic was preheated to a temperature of at least 1600°C during the forming process. Within the scope of the study, crack-free samples with bending strength over 500 MPa were produced. It is stated that the produced samples have a fine-grained, two-phase microstructure consisting of tetragonal zirconia and alpha-alumina. In the said study, it was stated that the production of high-strength ceramic components could be achieved by using Al2O3 and ZrO2 ceramic materials and that it would pioneer industrial applications.

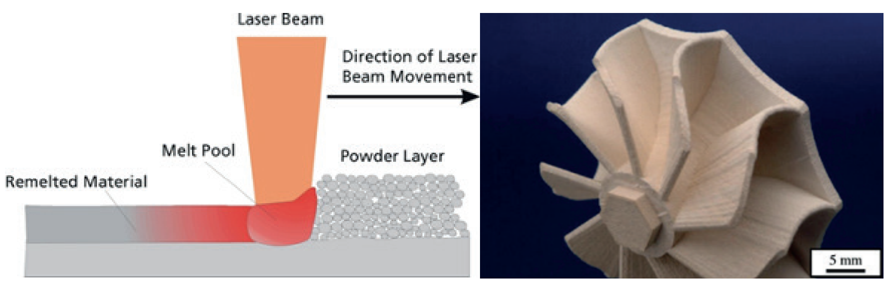

Figure 2. A- 3D Melting Method with SLM, B- Part made by SLM out of 80wt.% zirconia/20wt.% alumina (no preheating) [10].

In a review article by Lakhdar et al. on additive manufacturing (AM) of advanced ceramics; They emphasized the importance of minimizing the formation of residual porosity while preventing crack formation, which remains one of the main challenges of advanced ceramics in AM. Among currently available AM technologies, only a few processes allow the successful and reliable production of dense ceramic parts without any undesirable microporosity, while most technologies are only suitable for creating porous structures. Therefore, research and development efforts in the ceramic AM community have for several years been primarily focused on applications where porosity is beneficial, with a strong emphasis on porous components for biomedical applications and, in particular, scaffolds for tissue engineering [11]. Carloni et al. In their study, they produced transparent alumina ceramics using post-processing steps such as molding, vacuum sintering and polishing with an extrusion-based 3D printer. Within the scope of the study, manufacturable powder mixtures and 3D manufacturing parameters were optimized to produce quality bodies. They showed that two-stage vacuum sintering samples increased density while decreasing grain size, thus increasing the transparency of sintered alumina ceramics compared to single-step sintering samples. Two-stage vacuum sintered alumina ceramics stated that they achieved 70% total transmittance at 800 nm and relative density values higher than 99%. They demonstrated the ability of 3D AM manufacturing to compete with traditional transparent ceramic forming methods, as well as the additional benefit of freedom in the design and production of complex shapes [12]. Ceramics represent a new frontier for these LAM systems with many challenges and research needs. However, the material properties offered by ceramics compared to polymers and metals make the additive manufacturing of ceramic components an attractive engineering opportunity for many other technology fields such as aerospace and defense [13].

When the literature is examined in general, the studies on ceramics of the technology, which is quite new and has names such as Laser additive manufacturing and Laser 3D Printing, are limited. In the sintering of ceramics with this method, the problem of crack and pore formation caused by thermal stresses remains [14]. In addition, studies on the production of 3D ceramic materials with SLM and the determination of the energy absorption and damage behavior of hybrid sandwich composite panels produced with these materials under impact loads are very limited.

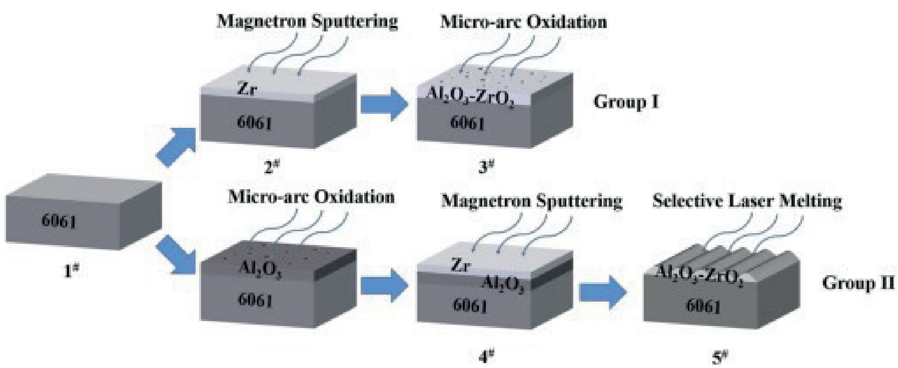

Figure 3. Schematic diagram of sample preparation used to test the mechanical properties of the structure formed by coating Al2O3 - ZrO2 layers with Micro-Arc Oxidation (MAO) and Selective Laser Melting (SLM) [14].

In conclusion; Ceramic products have been produced for decades using traditional techniques such as extrusion, kiln sintering and casting. However, these methods have several disadvantages in terms of possible shape and structure, which limit their range of application. The emergence of laser additive manufacturing (LAM) provides a significant opportunity to create ceramic components with much greater design freedom. This technology enables the creation of ceramic components that not only meet the increasing material requirements of aerospace applications but also offer new opportunities in terms of complex structures. The aim of this study is to investigate the usability of the production of ceramic materials such as Al2O3 and ZrO2 by selective laser melting 3D printing method for ballistic purposes. This study aims to increase ballistic protection capacity by offering a new approach in the production of ceramic materials used in the defense industry.

2. Ballistic Ceramics and Armor Applications

Focusing on the mechanical properties and performance criteria of the most commonly used ballistic ceramics, including alumina, silicon carbide and boron carbide, it can be seen that the main factors affecting the ballistic performance of ceramic materials are, in particular, hardness and fracture toughness. Additionally, the effect of functionally graded materials such as Al2O3-ZrO2 on the ballistic resistance capacity should also be examined. The effect of ceramic properties and penetration depth test parameters on the ballistic performance of armor ceramics are the most important critical factors that determine the effectiveness of ceramic materials in ballistic applications [15].

Dresch et al. A review conducted by provides a comprehensive analysis of the mechanical properties and ballistic behavior of ceramic materials and the suitability of these materials for armor applications (Figure 4). They also compared conventionally sintered and layered alumina and examined the ballistic behavior of these materials in detail. The research further emphasizes the development and optimization of ceramic-based ballistic protection systems [15].

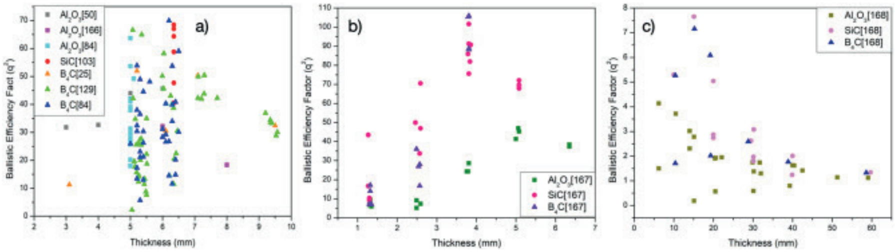

Figure 4. Relationship between ballistic efficiency factor and ceramic thickness. a) 7.62 AP; b) 0.30 AP M2; c) Rod. Data obtained from references [15].

Al2O3 is widely used as a ceramic material because it shows high strength and hardness. ZrO2 is often added to increase the durability of such a material. Huang et al. In a study by et al., they mixed Al2O3 and ZrO2 to formulate functionally graded materials (FGMs). Four-layer and eleven-layer Al2O3-ZrO2 FGMs were obtained from Al2O3 and ZrO2 mixtures by sintering at 1500 °C. They also designed experiments by mixing various ratios of Al2O3 and ZrO2 to analyze fracture toughness and hardness. As a result, they revealed that the 90% Al2O3 - 10% ZrO2 plate exhibited a hardness of 15.12 GPa, and the 50% Al2O3 - 50% ZrO2 plate achieved a fracture toughness as high as 4.7 MPa m0.5 [16].

2.1. Specific Properties of Al2O3 and ZrO2 Ceramic Materials for Ballistic Applications

Al2O3 (alumina) and ZrO2 (zirconia) ceramic materials have specific properties that make them suitable for ballistic applications. These features include:

1. Hardness: Alumina and zirconia ceramics exhibit high hardness, making them resistant to penetration and deformation when subjected to high-speed impacts. This feature is necessary to provide effective ballistic protection.

2. Impact Resistance: Combining the hardness of alumina with the durability of zirconia, zirconia-toughened alumina (ZTA) ceramic materials show excellent impact resistance. This property is very important to withstand the impact of high-speed bullets and fragments.

3. Wear Resistance: ZTA ceramic materials are known for their wear resistance, which is useful for maintaining the integrity and effectiveness of ballistic armor over time, especially in corrosive environments.

4. Fracture Toughness: The combination of zirconia and alumina in composite ceramics contributes to increased fracture toughness, allowing the material to absorb energy and resist crack propagation when exposed to ballistic impacts.

5. Microstructure: The microstructure of ZrO2-Al2O3 composite ceramics plays an important role in determining their mechanical properties, including hardness and fracture toughness. The microstructural properties of these ceramics are critical in terms of their ballistic resistance capabilities.

6. Mechanical Properties: The mechanical properties of alumina-based ceramics, including hardness and fracture toughness, are essential for their performance in ballistic applications. These properties are evaluated to evaluate the material's ability to withstand ballistic impacts.

In summary, the specific properties of Al2O3 and ZrO2 ceramic materials, such as hardness, impact resistance, wear resistance and fracture toughness, make them very suitable for ballistic applications. These properties enable ceramics to effectively resist penetration, absorb energy, and maintain their structural integrity when subjected to high-velocity impacts, making them valuable materials for ballistic armor and protective applications [16-18].

2.2 Ballistic Ceramics and the Importance of Developing These Ceramics as Armor Plates

Nowadays, the importance of ceramic materials developed for ballistic applications in the defense industry is increasing. These ceramics are preferred especially on the front surfaces of composite and hybrid composite plates due to their superior mechanical properties. The limitations of ceramic materials obtained by traditional production methods encourage the use of 3D printing technologies in the production of ceramic materials. In this context, the production of ceramic materials, especially Al2O3 (alumina) and ZrO2 (zirconia), by selective laser melting 3D printing method is of great importance to evaluate potential applications for ballistic purposes. Future research could focus on improving the surface quality of manufactured components, solving problems with cold powder deposition on pre-heated ceramics, further increasing mechanical strength, and transferring the technology from laboratory scale to industrial application.

Ballistic ceramics are the preferred materials for armor plates due to their high hardness and low density. Ballistic properties of ceramics such as boron carbide and alumina are examined by methods such as elemental analysis, phase analysis, microstructure analysis, density, pore analysis and three-point bending test [19]. The ballistic performance of ceramics depends on factors such as armor thickness, plate thickness and support plate. The armor thickness should be at least the radius of the bullet and the front ceramic plate thickness used should be 1/3 of the total armor thickness [20]. The ballistic performance of ceramic armor with concave and flat surface shapes is examined using numerical modeling methods. Modern armors are generally designed as a combination of a hard front surface with a ceramic layer and a fiber-reinforced back plate [21].

3. Comparison of Ceramic and Other Armor Plates in Terms of Ballistics

Ceramic-based armor plates offer many advantages in terms of ballistic performance compared to other types of armor plates. Ceramics such as boron carbide and silicon carbide are known for their high hardness, allowing them to effectively fragment or deform the core of an incoming projectile, dissipating its energy and stopping penetration. This feature makes ceramic armor plates highly effective against armor-piercing bullets designed to penetrate metal armor. Additionally, ceramic armor plates are lighter than traditional metal armor, providing the user with better mobility and reducing fatigue. However, a potential disadvantage of ceramic armor is its brittleness, which can be reduced by using a layered backplate to increase ballistic performance [22].

Research has shown that the ballistic efficiency of ceramic armor is affected by factors such as material composition, plate size, design and construction. For example, the hardness of the ceramic material, the depth of substrate deformation, and the resistance of the plates to brittle fracture are critical factors affecting the ballistic performance of the armor [23]. Additionally, it has been found that the layer structure of laminated ceramic plates significantly affects their ballistic performance, with studies showing the effectiveness of layered ceramic composites for body armor applications [24].

In summary, ceramic-based armor plates exhibit superior ballistic performance due to their high hardness, which allows them to effectively dissipate the energy of incoming bullets, and their lighter weight than metal armor. Ongoing research continues to focus on optimizing the design and structure of ceramic armor plates to further increase their ballistic efficiency and overall protective ability [25].

4. Feasibility of Ceramic Material Production with SLM

SLM (Selective Laser Melting) technology is a method whose usability is being investigated in the production of ceramic materials. This technology provides higher precision and control in the production of ceramic materials than traditional methods. The SLM method is based on the principle of melting the powders used in the production of ceramic materials with a laser and combining them layer by layer. This method provides less waste and higher efficiency in the production of ceramic materials. The mechanical properties of ceramic materials produced by SLM depend on factors such as hardness, density, porosity and thermal behavior. Therefore, the ballistic performance of ceramic materials produced by SLM depends on factors such as material properties and design. Since SLM technology provides higher precision and control in the production of ceramic materials, its usability in high-performance applications such as ballistic armor plates is being investigated.

Although the SLM method is a widely used method for 3D printing of metallic materials, some difficulties are encountered when working with ceramics. The high melting points and brittle nature of ceramics make it difficult to process ceramics with SLM compared to traditional metal 3D printing processes. Additionally, the high thermal conductivity of ceramics may affect the laser melting process and cause undesirable thermal stresses [15].

5. Conclusion and Evaluation

Selective laser melting (SLM) is a promising technology for ceramic 3D printing, but it also poses many challenges. One of the main challenges is the difficulty of obtaining high-density ceramic parts due to the high porosity of printed parts. This is because the ceramic powders of the SLM process have a high melting point, which can cause voids and defects in the printed parts. Another challenge is the limited number of ceramic materials that can be used in SLM. The process requires materials that can melt and solidify quickly, which limits the range of ceramic materials that can be used. Additionally, the high melting temperatures of some ceramic materials can cause thermal stresses during the printing process, leading to cracking and deformation of printed parts. Additionally, the SLM process for ceramic materials requires precise control of laser power, scanning speed, and powder bed temperature to achieve the desired properties of the printed parts. Optimization of these parameters is critical to obtaining high-quality ceramic parts with the desired properties. Despite these challenges, the potential benefits of SLM for ceramic 3D printing are significant. The technology offers the ability to produce complex ceramic parts with high precision and accuracy that are difficult to achieve with traditional manufacturing methods. Additionally, SLM can enable the production of customized ceramic parts with unique geometries and properties that can be tailored to specific applications.

In conclusion, while SLM presents several challenges for ceramic 3D printing, the potential benefits of this technology make it an attractive option for the production of high-performance ceramic parts. Further research and development is needed to overcome the challenges associated with SLM for ceramic materials and fully realize the potential of this technology for ceramic 3D printing. This study reveals the advantages of production of ceramic materials by selective laser melting 3D printing compared to traditional production methods and their potential applications for ballistic purposes. The main issues that need to be studied are the manufacturability of ceramic materials such as Al2O3 and ZrO2 by 3D printing, optimizing production conditions, their effect on material properties and their contribution to ballistic performance. The aim of the study is to present a new approach in the production of ceramic materials used in the defense industry. This new production technique, based on melting and solidifying high-performance ceramic material, has some significant advantages compared to laser sintering techniques or other production techniques based on solid-state sintering processes.

REFERENCES

[1] Z. Chen, Z. Li, J. Li, C. Liu, C. Lao, Y. Fu, C. Liu, Y. Li, P. Wang, Y. He, 3D printing of ceramics: a review, J. Eur. Ceram. Soc., 39 (4) (2019), pp. 661-687, https://doi.org/10.1016/j.jeurceramsoc.2018.11.013 .

[2] B. Lu, D. Li, X. Tian, Development trends in additive manufacturing and 3D printing Engineering, 1 (1) (2015), pp. 85-89, https://doi.org/10.15302/J-ENG-2015012 .

[3] T. Ngo, A. Kashani, G. Imbalzano, K. Nguyen, D. Hui,, Additive manufacturing (3D printing): a review of materials, methods, applications and challenges, Compos. Part B, 143 (2018) https://doi.org/10.1016/j.compositesb.2018.02.012 .

[4] K.V. Wong, A. Hernandez, A review of additive manufacturing, ISRN Mech. Eng., 2012 (4) (2012), pp. 1-10 https://doi.org/10.5402/2012/208760 .

[5] M. Bechthold, Ceramic prototypes - design, computation, and digital fabrication, Inf. Constr., 68 (544) (2016), pp. 1-11 DOI: https://doi.org/10.3989/ic.15.170.m15 .

[6] A. Zocca, P. Colombo, C.M. Gomes, J. Günster, Additive manufacturing of ceramics: issues, potentialities, and opportunities, J. Am. Ceram. Soc., 98 (7) (2015), pp. 1983-2001 https://doi.org/10.1111/jace.13700 .

[7] L.J. Kumar, C.G. Krishnadas Nair, Current trends of additive manufacturing in the aerospace industry, D.I. Wimpenny, P.M. Pandey, L.J. Kumar (Eds.), Advances in 3D Printing & Additive Manufacturing Technologies, Springer Singapore, Singapore (2017), pp. 39-54 https://doi.org/10.1007/978-981-10-0812-2_4 .

[8] A.A. Zadpoor, J. Malda, Additive manufacturing of biomaterials, tissues, and organs, Ann. Biomed. Eng., 45 (1) (2017), pp. 1-11 https://doi.org/10.1007/s10439-016-1719-y .

[9] Qi Liu. Etude sur fusion laser sélective de matériau céramique Zircone Yttriée. Autre. Université de Technologie de Belfort-Montbeliard, (2013). Français. ffNNT : 2013BELF0212ff https://theses.hal.science/tel-00976254 .

[10] Wilkes, J., Hagedorn, Y., Meiners, W. and Wissenbach, K., Additive manufacturing of ZrO2-Al2O3 ceramic components by selective laser melting, Rapid Prototyping Journal, Vol. 19 No. 1, (2013), pp. 51-57. https://doi.org/10.1108/13552541311292736 .

[11] Y. Lakhdar, C. Tuck, J. Binner, A. Terry, R. Goodridge, Additive manufacturing of advanced ceramic materials, Progress in Materials Science, Volume 116, (2021), 100736, ISSN 0079-6425, https://doi.org/10.1016/j.pmatsci.2020.100736 .

[12] David Carloni, Guangran Zhang, Yiquan Wu, Transparent alumina ceramics fabricated by 3D printing and vacuum sintering, Journal of the European Ceramic Society, Volume 41, Issue 1, (2021), Pages 781-791, ISSN 0955-2219, https://doi.org/10.1016/j.jeurceramsoc.2020.07.051.

[13] A. Goulas, R.J. Friel, Laser sintering of ceramic materials for aeronautical and astronautical applications, Editor(s): Milan Brandt, In Woodhead Publishing Series in Electronic and Optical Materials, Laser Additive Manufacturing, Woodhead Publishing, (2017), Pages 373-398, ISBN 9780081004333, https://doi.org/10.1016/B978-0-08-100433-3.00014-2.

[14] Wei Shao, Cancan Liu, Qiaojun Wu, Hongtao Li, **L.A. Angurel,** G.F. de la Fuente, Bailing Jiang, Comparison of in-situ oxidation behavior of Zr by micro-arc oxidation and selective laser melting, Journal of the European Ceramic Society, Volume 42, Issue 14, (2022), Pages 6703-6712, https://doi.org/10.1016/j.jeurceramsoc.2022.07.005.

[15] Alexander B. Dresch, Janio Venturini, Sabrina Arcaro, Oscar R.K. Montedo, Carlos P. Bergmann, Ballistic ceramics and analysis of their mechanical properties for armour applications: A review, Ceramics International,Volume 47, Issue 7, Part A, (2021), Pages 8743-8761, https://doi.org/10.1016/j.ceramint.2020.12.095 .

[16] Chin-Yu Huang, Yu-Liang Chen, Effect of mechanical properties on the ballistic resistance capability of Al2O3-ZrO2 functionally graded materials, Ceramics International, Volume 42, Issue 11, (2016), Pages 12946-12955, ISSN 0272-8842, https://doi.org/10.1016/j.ceramint.2016.05.067 .

[17] Xiaoyan Liu, Bin Zou, Hongyu Xing, Chuanzhen Huang, The preparation of ZrO2-Al2O3 composite ceramic by SLA-3D printing and sintering processing, Ceramics International, Volume 46, Issue 1, (2020), Pages 937-944, ISSN 0272-8842, https://doi.org/10.1016/j.ceramint.2019.09.054.

[18] Jones, TL, Vargas-Gonzalez, LR, Scott, B, Goodman, B, Becker, B. Ballistic evaluation and damage characterization of 3-D printed, alumina-based ceramics for light armor applications. *Int J Appl Ceram Technol*. (2020); 17: 424–437. https://doi.org/10.1111/ijac.13428.

[19] Koç (Güngör) S. and Akçay B., "B4C ve Al2O3 seramik plakalarının balistik özelliklerinin incelenmesi", Politeknik Dergisi, 25(3): 991-996, (2022), https://doi.org/10.2339/politeknik.801714.

[20] Güray Ersan, Kalemtaş Ayşe,. Seramik Esaslı Zırhlar ve Mekanik Modellemeleri. Seramik Türkiye Dergisi, Pages 98-104, (2015).

[21] AKDOĞAN, M.Akif, TÜRKBAŞ, O.Selim, Ballıstıc Protectıon Performance Of Curved And Plaın Ceramıc Armors, Gazi Journal of Engi-

neering Sciences, Pages: 91-106, (2016), https://dergipark.org.tr/tr/download/article-file/303148.

[22] Mengting Tan, Xianfeng Zhang, Wei Xiong, Chuang Liu, Guoqing Han, Yi Li, Influence of layered back plate on the ballistic performance of ceramic armor, Composite Structures, Volume 308, (2023), 116688, https://doi.org/10.1016/j.compstruct.2023.116688.

[23] ejdyś, M., Kośla, K., Kucharska-Jastrząbek, A. *et al.* Influence of ceramic properties on the ballistic performance of the hybrid ceramic–multi-layered UHMWPE composite armour. *J Aust Ceram Soc* **57**, 149–161 (2021). https://doi.org/10.1007/s41779-020-00516-7.

[24] Hong Y, Xie F, Xiong L, Yu M, Cheng X, Qi M, Shen Z, Wu G, Ma T, Jiang N. The Ballistic Performance of Laminated SiC Ceramics for Body Armor and the Effect of Layer Structure on It. *Applied Sciences*. (2021), 11(13):6145. https://doi.org/10.3390/app11136145.

[25] ARSLAN, K., & GÜNEŞ, R., Ballistic Impact Simulation of Ceramic/Metal Armor Structures, International Journal of Engineering Research and Development, 9(3), 12-20. (2017), https://doi.org/10.29137/umagd.371100 .