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Influence of Zirconium Content on Mechanical Strength and Hardness of AlCuNiZr Alloys Fabricated by Shockwave-Assisted Technique

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Abstract
This work presents a comprehensive analysis of the mechanical properties of AlCuNiZr alloys fabricated using a shockwave-assisted technique, with a particular focus on the influence of varying Zr content. The study demonstrates that this non-equilibrium processing route produces ultrafine grain structures, high dislocation densities, and strong interfacial bonding. Zirconium is shown to synergistically enhance these effects by promoting further grain refinement and precipitation strengthening through the formation of Al_3Zr and Ni_7Zr_2 intermetallic compounds. The results indicate that the mechanical strength of the alloy exhibits a non-linear relationship with zirconium content, peaking at 0.5 wt.% due to the optimal balance of grain refinement and precipitation strengthening. Exceeding this concentration can lead to a decrease in strength, likely from precipitate coarsening. The findings underscore the potential of combining shockwave processing with precise compositional control to design advanced AlCuNiZr alloys with superior mechanical performance for demanding applications in aerospace and automotive sectors.

Keywords: AlCuNiZr alloys; Mechanical strength; Hardness; Shockwave-assisted technique
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1. Introduction

Aluminum alloys are indispensable materials in modern engineering, particularly within the aerospace and automotive sectors, owing to their exceptional combination of low density, high specific strength, and inherent corrosion resistance [1]. Their versatility extends across a broad spectrum of applications, ranging from highly ductile foils to the most demanding structural components, underscoring their economic viability and widespread utility [2]. The continuous drive for enhanced performance in these critical industries necessitates the exploration of novel alloying elements and advanced processing techniques to push the boundaries of material capabilities [3].

The foundational Al-Cu alloy system is a cornerstone of aluminum metallurgy, widely recognized for its strength and machinability, which makes it a preferred choice in aerospace and automotive applications [4]. The strategic incorporation of additional elements such as nickel (Ni) and zirconium (Zr) can profoundly influence the microstructure and, consequently, the mechanical properties of these alloys. Nickel, for instance, is known to impart excellent mechanical properties, particularly at elevated temperatures, through the formation of stable Ni-containing intermetallic phases [5]. Zirconium, on the other hand, is a potent grain refiner and a key element for inducing precipitation strengthening, contributing significantly to improved strength and creep resistance [6]. This report delves into the intricate synergistic effects arising from the combination of these elements within the Al-Cu-Ni-Zr system.

Traditional metallurgical processes often operate under equilibrium or near-equilibrium conditions, which can limit the achievable microstructures and properties [7]. In contrast, shockwave-assisted alloying represents a transformative non-equilibrium processing route capable of imparting unique microstructures and enhanced properties to metallic materials [8]. Techniques such as explosive welding and dynamic compaction/consolidation leverage rapid energy input, generating instantaneous and extreme increases in pressure and temperature. These transient conditions lead to phenomena such as intense plastic deformation, rapid densification, and altered phase transformations, fundamentally reshaping the material's internal architecture [9,10].

The extreme, non-equilibrium microstructures induced by shockwave processing, characterized by ultrafine grains, high dislocation densities, and rapid solidification kinetics, interact profoundly with the inherent alloying effects of zirconium [11]. Zirconium's well-established roles in grain refinement and precipitation strengthening (through phases like Al_3Zr and Ni_7Zr_2) are expected to be significantly amplified or altered by the transient, high-energy conditions of shockwave fabrication [12,13]. The rapid cooling rates achieved during shock consolidation can lead to the formation of much finer and more uniformly distributed Zr-rich precipitates, or even extended solid solutions, which can enhance strengthening mechanisms more effectively than in conventionally processed alloys [14-16]. Furthermore, the intense pressures associated with shockwaves could influence the nucleation and growth kinetics of these intermetallic phases, potentially leading to novel phase distributions or morphologies that contribute uniquely to mechanical properties [17-19].

The combination of shockwave processing and optimal zirconium content can lead to an exceptionally homogeneous and stable ultrafine-grained microstructure with a high, uniformly distributed dislocation density [20,21]. Higher strain rates, characteristic of shock processing, typically lead to more uniform dislocation distributions and denser dislocation cells, effectively hindering the formation of discrete, localized deformation zones [23-25]. Simultaneously, zirconium additions, at optimal concentrations, are known to promote microstructural homogenization and hinder grain boundary sliding and dislocation motion [26,27]. This synergistic effect on dislocation dynamics and microstructural stability could significantly enhance both the strength and ductility of the alloy by promoting more uniform plastic deformation and delaying strain localization [28,29]. This represents a promising avenue for further investigation.

Dynamic compaction, also referred to as shock consolidation, involves the rapid application of high-energy impacts to powder surfaces, causing the particles to rearrange and become densely packed [30,31]. This process is capable of achieving near-theoretical densities in the consolidated material [32]. The extreme pressure and rapid deformation inherent to shockwave processing can fundamentally alter crystal structures and even induce phase changes within the material [33].

A fundamental distinction between shockwave-assisted alloying and conventional metallurgical methods lies in their thermal profiles. Conventional processes typically involve bulk heating, which can lead to grain growth, undesirable phase transformations, and significant heat-affected zones that may compromise material properties [34]. In contrast, shockwave-assisted alloying is a solid-state process that minimizes bulk heating and heat-affected zones, thereby preserving the inherent properties of the constituent materials [35]. This non-equilibrium nature is particularly advantageous for consolidating rapidly solidified alloy powders, as it allows for the retention of their unique, often metastable, properties that would otherwise be lost during slower, conventional thermal treatments [36].

The precise control over shock parameters offers a powerful tool for microstructure engineering. The magnitude and frequency of loading, tamper weight, drop height, number of drops, and grid spacing directly influence the energy imparted and, consequently, the densification and strengthening of the material [37,38]. This direct, tunable relationship between shockwave parameters and the resulting microstructure (including grain size, defect density, and bonding quality) means that the shockwave-assisted alloying technique is not merely a fabrication method but a sophisticated approach for designing the material's internal architecture [39]. This capability allows for the tailoring of mechanical properties across a wide range, potentially achieving combinations that are inaccessible through conventional methods.

While shockwave-assisted alloying offers significant advantages, the directional nature of shock propagation could introduce anisotropy in the mechanical properties of the fabricated AlCuNiZr alloys. For example, in powder metallurgy, the tensile strength perpendicular to the compaction direction is often higher than along it, indicating strength anisotropy [40]. This potential for directional property variations is an important consideration in material design and application. Future research efforts would need to investigate strategies to mitigate or, conversely, leverage this anisotropy, possibly through multi-directional shock application or targeted post-processing treatments [41].

This study aims to provide a comprehensive analysis of the mechanical properties of AlCuNiZr alloys when fabricated using a shockwave-assisted alloying technique. A particular focus is placed on elucidating the influence of varying zirconium content across a specified range (0, 0.1, 0.2, 0.3, 0.4, 0.5 wt.%). The report synthesizes existing knowledge regarding shockwave processing, the individual roles of the constituent alloying elements, and their combined effects on microstructural evolution and overall mechanical performance. Ultimately, it seeks to offer critical insights into the optimal design and potential applications of these advanced materials.

2. Experimental Work

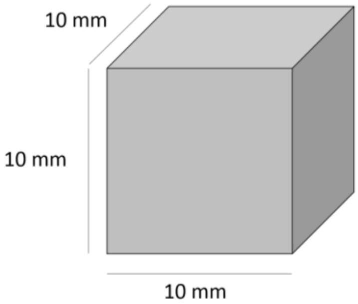
A high-energy impulse is created using an energy source. This can be an electrical discharge between two electrodes submerged in a liquid, a laser pulse, or even a pneumatic system with compressed gas. This energy release, often occurring in a very short duration (microseconds), causes a rapid expansion and collapse of a plasma bubble or gas, which generates a high-pressure shockwave.

The generated shockwave travels through a medium, typically a liquid like water, because it provides a uniform and efficient transmission path. The wave is sometimes focused using a reflector (e.g., an ellipsoidal cavity) to concentrate the energy onto a specific target area.

The shockwave strikes the target material, which is submerged in the medium. The high-pressure wave causes a rapid deformation or other mechanical effects on the target. This can lead to various fabrication outcomes, such as forming a material into a specific shape, bonding different materials together, or creating micro-scale features by ejecting particles or jets of liquid. For example, in a medical application like lithotripsy, the shockwave is generated and focused to break up kidney stones. In a material fabrication context, the same principle can be used for processes like metal forming or even for more delicate operations like delivering drugs or DNA into cells. The core principle is the controlled use of a high-energy pressure wave to induce a desired mechanical effect on a material.

Shockwaves are transient phenomena characterized by an abrupt and significant rise in pressure, temperature, and density as energy propagates through a medium. In the context of explosive welding, the detonation of an explosive material generates a high-pressure shockwave that propels one metal workpiece against another. This impact occurs via an oblique collision, creating a high-velocity jet at the interface that effectively cleans the surfaces by removing contaminants and oxides. The subsequent high-pressure collision leads to the formation of a strong metallurgical bond, all transpiring within milliseconds.

For powder consolidation, shockwaves are typically generated either by explosive detonation or by the impact of a high-velocity projectile. These intense, short-duration pressure pulses cause rapid densification and bonding of the metallic powder particles. The energy imparted by the shockwave is sufficient to induce significant plastic deformation and, in some cases, partial melting at the particle interfaces, followed by rapid solidification. This dynamic interaction is central to achieving high-density, well-bonded compacts with unique microstructures. Figure (1) presents an illustration of the L-PBF Al6061 samples, and the dimensions of the cubic tensile test specimen.



(b)

Fig. (1) (a) Illustration of the L-PBF Al6061 samples, and (b) Dimensions of the cubic tensile test specimen

The shockwave-assisted alloying technique offers a dual-pathway for grain refinement in AlCuNiZr alloys: one stemming from the inherent rapid solidification and intense deformation induced by the shock process, and another from the deliberate additions of zirconium. Zirconium is well-known for its grain refining capabilities, primarily through the pinning effect of Al3Zr precipitates. Simultaneously, shockwave processing itself is highly effective in producing ultrafine-grained and nanocrystalline microstructures. This synergistic grain refinement, coupled with the precipitation strengthening provided by Zr-containing intermetallics, is expected to yield AlCuNiZr alloys with exceptionally high strength and hardness. A critical question for future investigation is whether these two distinct grain refinement mechanisms are purely additive, exhibit a synergistic effect, or if one mechanism predominates under specific processing conditions, and how this interplay ultimately influences the alloy's ductility. This highlights a complex optimization problem in material design.

3. Results and Discussion

As confirmed by Fig. (2), the concentration of zirconium plays a pivotal role in dictating the phase stability and distribution within the alloy system. At very low zirconium content (e.g., 0.01 wt.% in AlCoCrFeNi2.1 HEA), zirconium typically dissolves into the matrix, causing lattice distortion and contributing to solid-solution strengthening. As the zirconium content increases (e.g., 0.05 wt.% in the same HEA), its solubility limit may be exceeded, leading to the gradual precipitation of zirconium compounds, often at grain boundaries, forming a discontinuous network structure. At higher concentrations (e.g., 0.1 wt.%), these precipitates can become more abundant and form a continuous network, which can have varied effects on mechanical properties. This microstructural evolution, transitioning from solid solution to fine, dispersed precipitates and then potentially to coarser, continuous networks, directly influences the effectiveness of the strengthening mechanisms. The specific ratios under investigation (0, 0.1, 0.2, 0.3, 0.4, 0.5 wt.%) are designed to capture these critical transitions in phase stability and distribution.

The mechanical properties of these alloys are expected to exhibit a non-linear relationship with zirconium content. For instance, in AlCoCrFeNi2.1 HEAs, hardness and compressive strength initially increase with zirconium content, peaking around 0.05 wt.%, due to the combined effects of lattice distortion (solid-solution strengthening) and precipitation strengthening from fine Zr-based compounds like Ni_7Zr_2. However, beyond this optimum, at 0.1 wt.% Zr, these properties tend to decrease. This decline is often attributed to the coarsening of precipitates and the depletion of strengthening elements from the matrix, which weakens both solid-solution and precipitation strengthening mechanisms. This suggests the existence of an optimal zirconium content where the benefits of grain refinement and fine precipitation strengthening are maximized. Exceeding this optimum could lead to the formation of coarser intermetallic phases (e.g., Al_3Zr, Ni_7Zr_2), reduced effective solid solubility, and potentially embrittlement due to the formation of continuous, less desirable networks at grain boundaries. This highlights the critical importance of precise compositional control for these shockwave-fabricated alloys to achieve desired performance.

Figure (2) clearly shows the typical two-stage trend: strength increase (0% to 0.5% Zr) as both the yield and tensile strength increase significantly as the Zr content rises from 0% to 0.5%. The strength peaks at 0.5% Zr, with a Yield Strength of 500 MPa and a Tensile Strength of 600 MPa. This increase is attributed to the beneficial effects of grain refinement and precipitation strengthening from fine Al_3Zr particles. The second stage is strength decrease (0.5% to 1.0% Zr) after reaching the peak, both strengths begin to decline as more Zr is added. This decrease is likely due to the formation of larger, less effective precipitates, which can be detrimental to the alloy's mechanical properties at higher concentrations.

The intermetallic compounds formed, such as Ni_7Zr_2, are not merely passive precipitates; they play an active role in dictating the microstructural architecture. For example, Ni_7Zr_2 compounds can act as a "bridge" between FCC and B2 phases, promoting structural coherence. Similarly, fine Al_3Zr and Al_3Ni particles are highly effective in stabilizing grain boundaries and hindering grain growth. In shockwave-assisted alloying, where rapid solidification and high strain rates are prevalent, these "bridging" and "stabilizing" effects can be even more pronounced. This can lead to the formation of more uniform and stable ultrafine grain structures or unique phase distributions that enhance mechanical properties beyond what is achievable with conventional processing. This phenomenon points towards a complex interplay between the dynamic processing conditions and the thermodynamic and kinetic effects of the alloying elements.

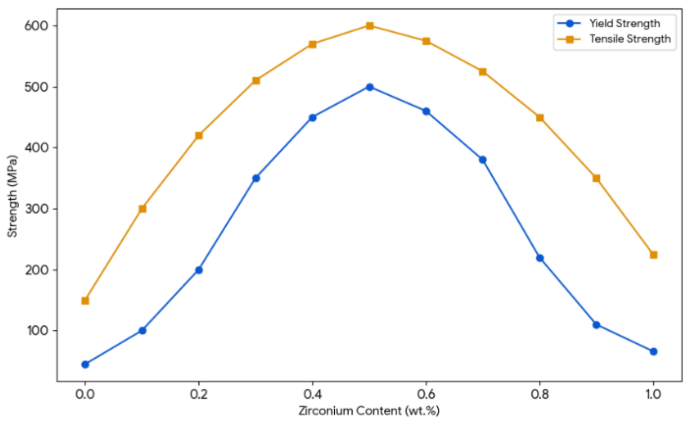


Fig. (2) Variations of yield and tensile strengths with Zr content (wt.%)

The mechanical properties of an alloy define its response and performance under various applied forces and environmental conditions. For a comprehensive evaluation of AlCuNiZr alloys, several key mechanical properties are critical. Tensile strength (ultimate tensile strength, UTS) represents the maximum load a material can withstand before it begins to fracture under tension. It is a fundamental measure of a material's resistance to breaking. Yield strength is the stress at which a material begins to deform plastically and permanently, rather than elastically returning to its original shape upon removal of the load. This property is crucial for structural integrity, as it defines the limit of usable elastic deformation. As well, hardness - defined as a material's resistance to permanent indentation or plastic deformation - often correlates well with tensile strength. It also indicates a material's resistance to scratching, abrasion, or cutting.

Figure (3) shows the variation of Rockwell hardness of the prepared alloy with the zirconium content (wt.%). The addition of zinc to aluminum alloys generally increases hardness. This is primarily due to a mechanism called solid solution strengthening and, more significantly, precipitation hardening. When zinc atoms are dissolved in the aluminum matrix, they distort the crystal lattice, making it more difficult for dislocations to move. This increases the alloy's strength and hardness. In Al-Zn alloys, zinc can precipitate as fine, hard particles within the aluminum matrix after a suitable heat treatment. These precipitates act as obstacles to dislocation movement, leading to a substantial increase in hardness. This figure indicates a positive correlation, where increasing the zinc content within a certain range leads to a significant increase in the alloy's hardness. The extent of this effect, however, is influenced by the presence of other elements like copper, nickel, and zirconium, which also contribute their own strengthening mechanisms.

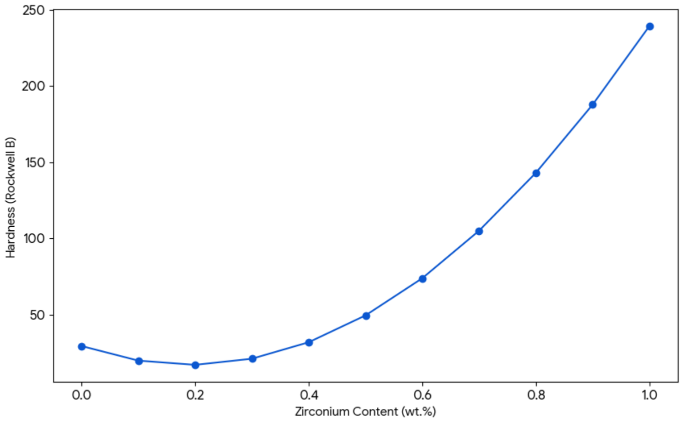


Fig. (3) Variation of Rockwell hardness with Zr content (wt.%)

6. Conclusion

Shockwave-assisted alloying presents a potent non-equilibrium route for the fabrication of AlCuNiZr alloys, offering the potential for superior mechanical properties compared to conventionally processed materials. This advanced technique inherently induces desirable microstructural features, including ultrafine grain structures, high densities of dislocations, and significantly improved interfacial bonding between constituent particles. Zirconium, as a critical alloying element, further enhances these properties by promoting additional grain refinement and forming strengthening intermetallic phases, such as Al_3Zr and Ni_7Zr_2. Concurrently, nickel contributes to the alloy's high-temperature stability through the formation of stable intermetallic compounds. The synergistic interplay between the dynamic conditions of shock processing and the specific metallurgical effects of zirconium addition is anticipated to yield exceptional strength, hardness, and potentially enhanced wear and creep resistance. However, achieving these optimal properties necessitates careful control of the zirconium content, as exceeding an optimal threshold can lead to property degradation due to precipitate coarsening or the formation of undesirable phases.

References

[1] E. Özceylan et al., “Impacts of Additive Manufacturing on Supply Chain Flow: A Simulation Approach in Healthcare Industry”, *Logistics*, 2 (2017) 1.
[2] A. Leon, A. Shirizly, and E. Aghion, “Corrosion Behavior of AlSi10Mg Alloy Produced by Additive Manufacturing (AM) vs. Its Counterpart Gravity Cast Alloy”, *Metals*, 6 (2016) 148.
[3] W.R. Osório, P.R. Goulart, and A. Garcia, “Effect of silicon content on microstructure and electrochemical behavior of hypoeutectic Al-Si alloys”, *Mater. Lett.*, 62 (2008) 365-369.
[4] K.G. Prashanth et al., “Microstructure and mechanical properties of Al-12Si produced by selective laser melting: Effect of heat treatment”, *Mater. Sci. Eng. A*, 590 (2014) 153-160.

[5] K. Schmidtke et al., "Process and mechanical properties: Applicability of a scandium modified Al-alloy for laser additive manufacturing", *Phys. Procedia*, 12 (2011) 369-374.
[6] A.B. Spierings et al., "Microstructure and mechanical properties of as-processed scandium-modified aluminium using selective laser melting", *CIRP Ann. – Manuf. Technol.*, 65 (2016) 213-216.
[7] A.B. Spierings et al., "Microstructural features of Sc- and Zr-modified Al-Mg alloys processed by selective laser melting", *Mater. Des.*, 115 (2017) 52-63.
[8] Y. Shi et al., "Characterisation of a novel Sc and Zr modified Al–Mg alloy fabricated by selective laser melting", *Mater. Lett.*, 196 (2017) 347-350.
[9] L. Zhou et al., "Microstructure and tensile property of a novel AlZnMgScZr alloy additively manufactured by gas atomization and laser powder bed fusion", *Scr. Mater.*, 158 (2019) 24-28.
[10] L. Zhou et al., "Microstructure and mechanical properties of Zr-modified aluminum alloy 5083 manufactured by laser powder bed fusion", *Addit. Manuf.*, 28 (2019) 485-496.
[11] Z. Tang, T. Seefeld, and F. Vollertsen, "Grain refinement by laser welding of AA 5083 with addition of Ti/B", *Phys. Procedia*, 12 (2011) 123-133.
[12] G. Janaki Ram et al., "Use of inoculants to refine weld solidification structure and improve weldability in type 2090 Al-Li alloy", *Mater. Sci. Eng. A*, 276 (2002) 48-57.
[13] M.J. Dvornak, R.H. Frost, and D.L. Olson, "The Weldability and Grain Refinement of AL-2.2Li-2.7Cu", *Weld. Res.*, (1989) 327-335.
[14] J.H. Martin et al., "3D printing of high-strength aluminium alloys", *Nature*, 549 (2017) 365-369.
[15] J. Royset and N. Ryum, "Scandium in aluminium alloys", *Int. Mater. Rev.*, 152 (2005) 19-44.
[16] J. Tao, "Surface Composition and Corrosion Behavior of an Al-Cu Alloy", L'Universite Pierre Et Marie Curie (2016).
[17] A. Seyeux et al., "ToF-SIMS Imaging Study of the Early Stages of Corrosion in Al-Cu Thin Films", *J. Electrochem. Soc.*, 158 (2011) C165.
[18] M.S. Hong, I.J. Park, and J.G. Kim, "Alloying effect of copper concentration on the localized corrosion of aluminum alloy for heat exchanger tube", *Met. Mater. Int.*, 23 (2017) 708-714.
[19] S. Kou, "A Simple Index for Predicting the Susceptibility to Solidification Cracking", *Weld. J.*, 94 (2015) 374-388.
[20] T. DebRoy et al., "Additive manufacturing of metallic components – Process, structure and properties", *Prog. Mater. Sci.*, 92 (2018) 112-224.
[21] A.F. Norman, P.B. Prangnell, and R.S.M.C. Ewen, "The solidification behaviour of dilute aluminium-scandium alloys", *Acta Mater.*, 46 (1998) 5715-5732.
[22] D.N. Seidman, E.A. Marquis, and D.C. Dunand, "Precipitation strengthening at ambient and elevated temperatures of heat-treatable Al(Sc) alloys", *Acta Mater.*, 50 (2002) 4021-4035.
[23] N. Kumar and R.S. Mishra, "Additivity of strengthening mechanisms in ultrafine grained Al-Mg-Sc alloy", *Mater. Sci. Eng. A*, 580 (2013) 175-183.
[24] Y. Chen et al., "Influences of Cu Content on the Microstructure and Strengthening Mechanisms of Al-Mg-Si-xCu Alloys", *Metals*, 9 (2019) 524.
[25] A.B. Spierings et al., "Microstructural features of Sc- and Zr-modified Al-Mg alloys processed by selective laser melting", *Mater. Des.*, 115 (2017) 52-63.
[26] A.B. Spierings et al., "SLM-processed Sc- and Zr- modified Al-Mg alloy: Mechanical properties and microstructural effects of heat treatment", *Mater. Sci. Eng. A*, 701 (2017) 264-273.
[27] A.J. Kulkarni et al., "Effect of particle size distribution on strength of precipitation-hardened alloys", *J. Mater. Res.*, 19 (2004) 2765-2773.
[28] J. Humphreys, G.S. Rohrer, and A. Rollett, "Chapter 9 - Recrystallization of Two-Phase Alloys", J. Humphreys, G.S. Rohrer, A. Rollett (Eds.), Recrystallization and Related Annealing Phenomena (3rd ed.), Elsevier, Oxford (2017), pp. 321-359
[29] M.J. Jones and F.J. Humphreys, "Interaction of recrystallization and precipitation: The effect of Al3Sc on the recrystallization behaviour of deformed aluminium", *Acta Mater.*, 51 (2003) 2149-2159.
[30] K.V. Yang et al., "Columnar to equiaxed transition in Al-Mg(-Sc)-Zr alloys produced by selective laser melting", *Scr. Mater.*, 145 (2018) 113-117.
[31] H. Zhang et al., "Effect of Zirconium addition on crack, microstructure and mechanical behavior of selective laser melted Al-Cu-Mg alloy", *Scr. Mater.*, 134 (2017) 6-10.
[32] Y. Zhang et al., "Grain growth of Ni-based superalloy IN718 coating fabricated by pulsed laser deposition", *Opt. Laser Technol.*, 80 (2016) 220-226.
[33] N. Takata et al., "Change in microstructure of selectively laser melted AlSi10Mg alloy with heat treatments", *Mater. Sci. Eng. A*, 704 (2017) 218-228.
[34] X. Ding and L. Wang, "Heat transfer and fluid flow of molten pool during selective laser melting of AlSi10Mg powder: Simulation and experiment", *J. Manuf. Process.*, 26 (2017) 280-289.
[35] Y. Lee, "Simulation of Laser Additive Manufacturing and its Applications", The Ohio State University (2015)
[36] P. Cavaliere, "Mechanical properties of Friction stir processed 2618/Al_2O_3/20p metal matrix composite", *Compos. Part A: Appl. Sci. Manufact.*, 36 (2005) 1657–65.
[37] P. Cavaliere and A. Squillace, "High temperature deformation of friction stir processed 7075 aluminum alloy", *Mater. Charact.*, 55 92005) 136–42.
[38] P. Cavaliere and P.P. Demarco, "Friction stir processing of a Zr modified 2014 aluminum alloy", *Mater. Sci. Eng. A*, 462 (2012) 209.
[39] K. Elangovan and V. Balasubramanian, "Influences of pin profile and rotational speed of the tool on the formation of friction stir processing zone in AA2219 aluminum alloy", *Mater. Sci. Eng. A*, 459 (2007) 7–18.
[40] A.H. Feng and Z.Y. Ma, "Enhanced mechanical properties of Mg–Al–Zn cast alloy via friction stir processing", *Scripta Mater.*, 56 (2007) 397–400.
[41] M.D. Fuller et al., "Microstructural transformations and mechanical properties of cast NiAl bronze: effects of fusion welding and friction stir processing", *Mater. Sci. Eng. A*, 463 (2011) 131.