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Quasi-Static and Dynamic Mechanical Properties of a Ti-6Al-4V Titanium Alloy Produced Using Unconventional Manufacturing Methods

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Abstract. The purpose of this paper was to determine the mechanical properties of a Ti-6Al-4V titanium alloy produced by traditional CIP (Cold Isostatic Pressing) and by LENS (Laser Engineered Net Shaping), an additive manufacturing process. A reference material, being a commercial Ti-6Al-4V alloy, was also tested. The strength test specimens were produced from a high-quality, Grade 5 titanium powder. Each specimen had its density, porosity, and hardness determined. Compression curves were plotted for the tested materials from the strength test results with static and dynamic loads. These tests were performed on an UTS (Universal Testing Machine) and an SHPB (Split Hopkinson Pressure Bar) stand. The test results obtained led to the conclusion that the titanium alloy produced by CIP had lower strength performance parameters than its commercially-sourced counterpart. The LENS-produced specimens outperformed the commercially-sourced alloy both in static and dynamic load conditions.

Keywords: titanium alloys, split Hopkinson pressure bar, LENS; additive manufacturing

1. INTRODUCTION

Titanium alloys find widespread use in various areas of life and engineering. Titanium is classified into 38 grades, with the 5 most commonly used numbered from 1 to 5. Grades 1 to 4 are pure titanium with precisely specified oxygen contents, while Grade 5 is the immensely popular titanium alloy, Ti-6Al-4V. All engineering applications of titanium benefit from its uniquely good combination of high mechanical strength, low specific gravity, and high corrosion resistance. The best example is the use of titanium in the construction of aerospace vehicles, where the deadweight reduction is the greatest challenge in the efforts to maximise range and speed. In shipbuilding, titanium is valued for its high mechanical strength and resistance to corrosion by salt water. Unfortunately, titanium and its alloys are expensive as structural materials. Considering the advantages of this metal, it is difficult to find a commercially reasonable alternative for many of its applications. An example is the chemical processing industry, where titanium or titanium alloy components enjoy a longer life than steel under the same aggressive ambient conditions. Aside from machine engineering, titanium alloys have found use in bioengineering as an alternative to chromium cobalt alloys. Endoprostheses made of Ti-6Al-4V, a high-purity Grade 5 titanium alloy. Following a number of tests it was demonstrated that titanium, when used as an implant material, is completely non-toxic and biocompatible in the human system, as human tissues grow uninhibited on titanium components, such as those used to bind fractured bones [1–8].

Until recently, the application of titanium alloys was limited in certain areas given the poor deformability of the material, especially for cold working [9]. However, recent years have seen the development of techniques related to the production of pure titanium alloy powders and the evolution of new, unconventional additive manufacturing (AM) processes based on powdered intermediates as well as new potential in the production of machine components from these forms of titanium alloys. Examples of the latest processes include LENS (Laser Engineered Net Shaping), SLS (Selective Laser Sintering) and SLM (Selective Laser Melting). These methods are relatively new and their full potential still remains unknown.

The reference literature includes examples of the applications possible from these manufacturing processes considered in the tests explained in this work, being powder metallurgy (CIP) and LENS. As yet there are no dynamic (impact strength) tests for the mechanical properties of the titanium alloys produced with these unconventional processes. The plastic deformation of materials under dynamic strain differs wildly from quasi-static strain. Dynamic deformation is first the effect of wave effects occurring in the material being strained. Moreover, the course of the strain is also an effect of the inertial forces manifested in the process.

The reaction of a material to plastic strain, which progresses at a strain rate of more than 10^3 s^{-1} can be very different from the material's behaviour under quasi-static conditions [10]. The complexity of the actions which govern the progress of dynamic strain in materials and the sheer difficulty of predicting their reaction to dynamic loads necessitates non-standard dynamic testing based on unconventional techniques. This is especially important for structural materials that are intended for machine parts operating under dynamic loads (like parts of weapons).

The aim of this paper is to assess the quasi-static and dynamic mechanical properties of a titanium alloy (Grade 5) produced using unconventional manufacturing processes: traditional CIP (Cold Isostatic Pressing) and highly advanced LENS. To achieve a comparative study, Ti-6Al-4V obtained by traditional forging, casting and roll engineering was also tested.

2. TEST METHODOLOGY

2.1. Manufacturing process of the material specimens

Two sets of material specimens were made of Ti-6Al-4V, by traditional CIP and modern LENS. The manufacturing process flowchart for the CIP-produced titanium alloy specimens is shown in Fig. 1.

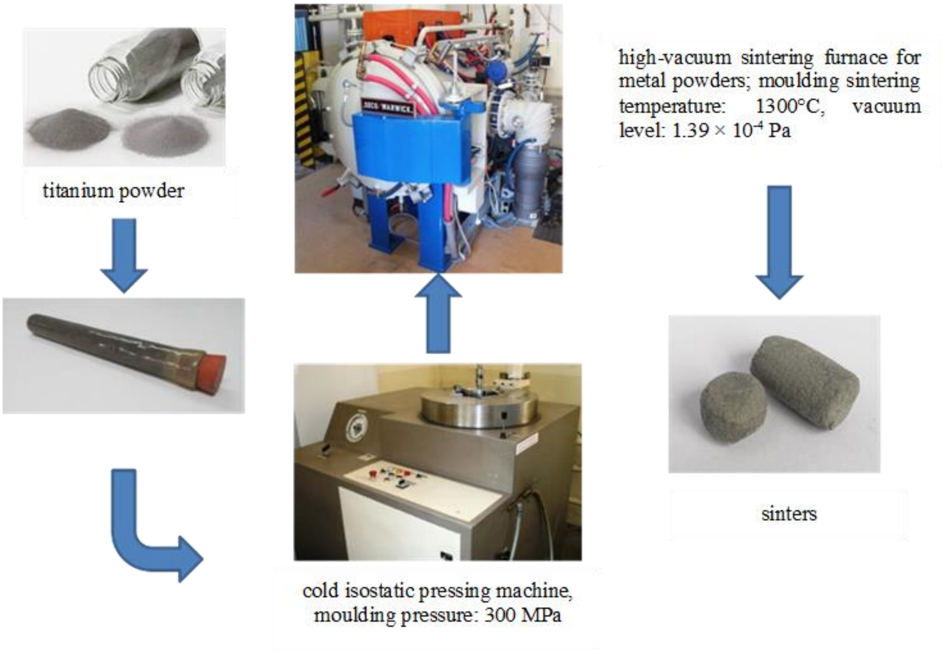


Fig. 1. Scheme of manufacturing Ti-6Al-4V alloy using classical method of powder metallurgy

The alloy powder was introduced into prepared and sealed moulds made of an elastic plastic. The moulds were moved to a CIP machine where the alloy powder was compacted and formed under a liquid pressure of 300 MPa into cylindrical mouldings. The last step of this process was the sintering of the mouldings in ceramic jackets, in a vacuum furnace held at 1300°C and a high vacuum of 10^{-4} Pa.

LENS (Laser Engineered Net Shaping) is a novel technology which facilitates the production of next-generation engineering materials. A LENS production process begins with the development of a 3D model of the product in CAD. The model is split into layers, each of equal and known thickness, and the LENS processing parameters are specified (laser beam output, powder feed rate, and laser head feed rate), which enables additive manufacturing of a part blank (intermediate) to achieve a mechanical performance similar to that of a solid body of the same material. The metal powder from which the part is manufactured is moved while entrained by a jet of inert gas (argon) into the nozzles of a LENS laser head. The metal powder is positioned directly at the laser beam focal spot; the laser energy remelts the powder particles, which are deposited layer by layer on the building substrate, and in this way creating the part.

LENS features many advantages, including the feasibility of fast production from metal powders with pre-planning of the microstructure, chemical composition, and/or phase composition of the manufactured material. LENS can produce composite workpieces or gradient-structured parts, the manufacturing of which in other processes would be virtually impossible. LENS can also be used for the reconditioning of machine components by the deposition material in layers at the locations where it was removed by operating wear [11, 12].

The primary advantage of the LENS MR-7 system is that it can be fed from four dispensers at the same time, using different metal powders. The thermal imaging camera installed inside of the build chamber and the LENS control software allow continuous monitoring of the molten pool temperature and management of the laser output power. [11, 12] The layout of the LENS system is shown in Fig. 2. Examples of the LENS-made products are shown in Fig. 3.

The final form of the specimens (cylinders ø4 x 2, 4 and 6 mm) was achieved by EDM on a BP 95d machine. The examples made on the EDM machine are shown in Fig. 4.

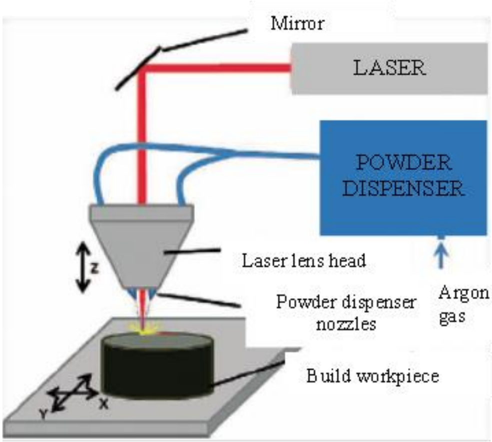


Fig. 2. Device scheme of LENS type [12]

Fig. 3. Ti-6Al-4V alloy specimens performed with LENS technology

Fig. 4. Test specimens made using the electrical discharge machining

2.2. Test procedure

The tests performed for this work included the examination of the material properties, including its strength. The material properties tested were density and porosity, and included metallographic inspection. The density of the materials was determined with a hydrostatic balance, with the porosity determined using a Nikon/METRIS XT H 225 ST micro-focus CT scanner. The polished sections were imaged under a JEOL JSM-5400 scanning electron microscope.

The testing of the titanium alloy mechanical properties involved hardness and compression tests under different load conditions, both quasi-static and dynamic. The hardness was tested on the Vickers scale with a micro strength testing machine (Zwick 3112). The quasi-static mechanical characteristics were determined from the experimental test data produced by an MTS Criterion C45 UTS. The UTS was operated with controlled displacement to ensure a steady strain rate for the tested materials. The strength tests were performed with two strain rate settings, 0.001 s^{-1} and 1 s^{-1}.

The high strain rate tests were performed with the SHPB (Split Hopkinson Pressure Bar) method. The SHPB test rig is illustrated in Fig. 5. This is the most common test practice for materials at high strain rates. An extensive specification of the method is given in [13]. The tensile SHPB is the only high strain rate dynamic test method which has a standardised procedure (PN-EN ISO 26203-1/2012) [14].

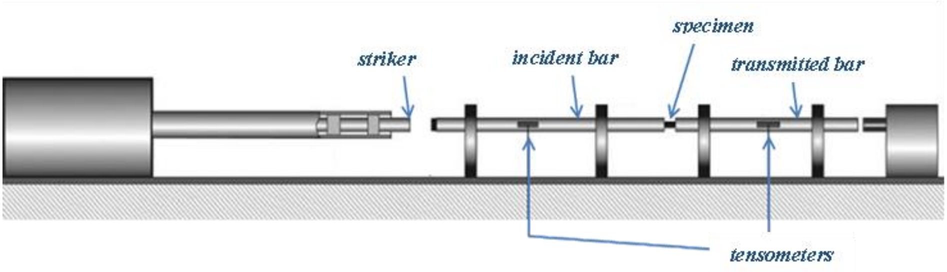


Fig. 5. Scheme of Split Hopkinson Pressure Bar system

A typical SHPB test comprises three bars: striker, the incident, and the transmitted bar, which are elastically strained during an SHPB test. Essentially, the test involves fixing the test specimen between the end faces of the incident bar and the transmitted bar, followed by wave-pattern loading of the specimen with the input bar being struck against the end of the incident bar. Based on the inputs propagating through the bars and picked up by a strain gauge measuring system, the dynamic compression curves can be plotted from the Kolsky equations [14, 15].

The tests were performed on a test stand, one of the assets of the Military University of Technology, Laboratory of Armament Technologies and Operation. The SHPB test system featured a mechanical subassembly, a measuring subassembly and a power supply. The mechanical subassembly was a system of two bars, each 1200 mm long and 12.05 mm of diameter, manufactured from MS 350 maraging steel, 54 HRC ($R_{0.2}$ = 2300 MPa). The concentric alignment of the bars was ensured by an arrangement of eight supports with linear bearings. The supports were installed on an optical dialling bench to enable precise adjustment of the support locations.

The mechanical subassembly also featured a pneumatic propulsion system which accelerated the 200 mm long input bar from 4 m/s to 30 m/s. The pneumatic propulsion system comprises a barrel 1150 mm long and with an internal diameter of 12.1 mm, a solenoid valve, and a pressurised supply tank with an electronic pressure gauge. The measuring subassembly comprises a SGA0BV5 two-channel strain gauge amplifier by Zakład Aparatury Elektronicznej "ATA" (Poland), an optoCONTROL ODC 1200/90 laser micrometer, and a LeCroy WJ354A digital oscilloscope. The strain waves generated in the bar were recoded with Vishay CEA-13-062UW-350 strain gauges, bonded to the opposite lateral surfaces of the incident and the receiver bars. The power supply component comprised of an air compressor with a vacuum pump for the input bar pneumatic propulsion system.

3. TEST RESULTS

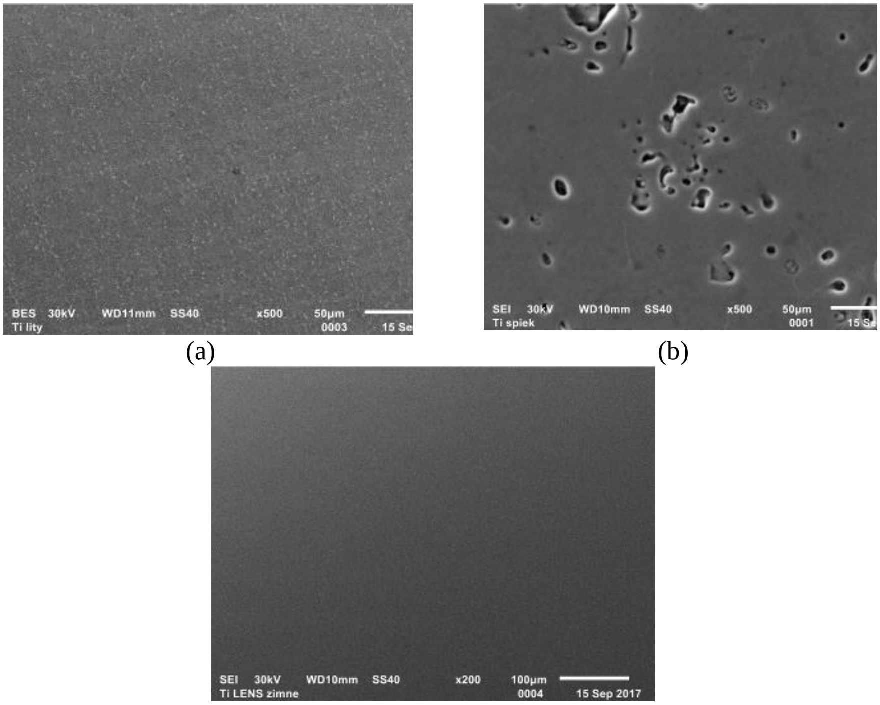
3.1. Physical parameters

The results of the material density, porosity, and hardness tests are given in Table 1. The microstructural images are shown in Fig. 6.

Table 1. Average values of density, porosity and hardness of materials

Ti-6Al-4V	**Density, ρ [g/cm^3]**	**Porosity [%]**	**HV1 hardness**
Metallurgical alloy	4.43	-	320
LENS	4.39	0.0006	355
PM-CIP	3.98	11.6	110

The test results indicate that the material of the LENS test specimen had properties very similar to those for commercially-sourced, metallurgically forged, cast and rolled Ti-6Al-4V. The density of the materials was approximately 4.4 g/cm^3 with the hardness of 320 HV1 and 355 HV1 for the metallurgical titanium alloy and the LENS titanium alloy, respectively. The sintered Ti-6Al-4V produced by CIP had a lower density, of around 4 g/cm^3, and consequently developed a higher porosity of approximately 12%. The presence of pores in the PM-CIP specimens was very evident in the microscopic images (Fig. 6b). The PM-CIP titanium alloy hardness was markedly lower and just at 110 HV1.



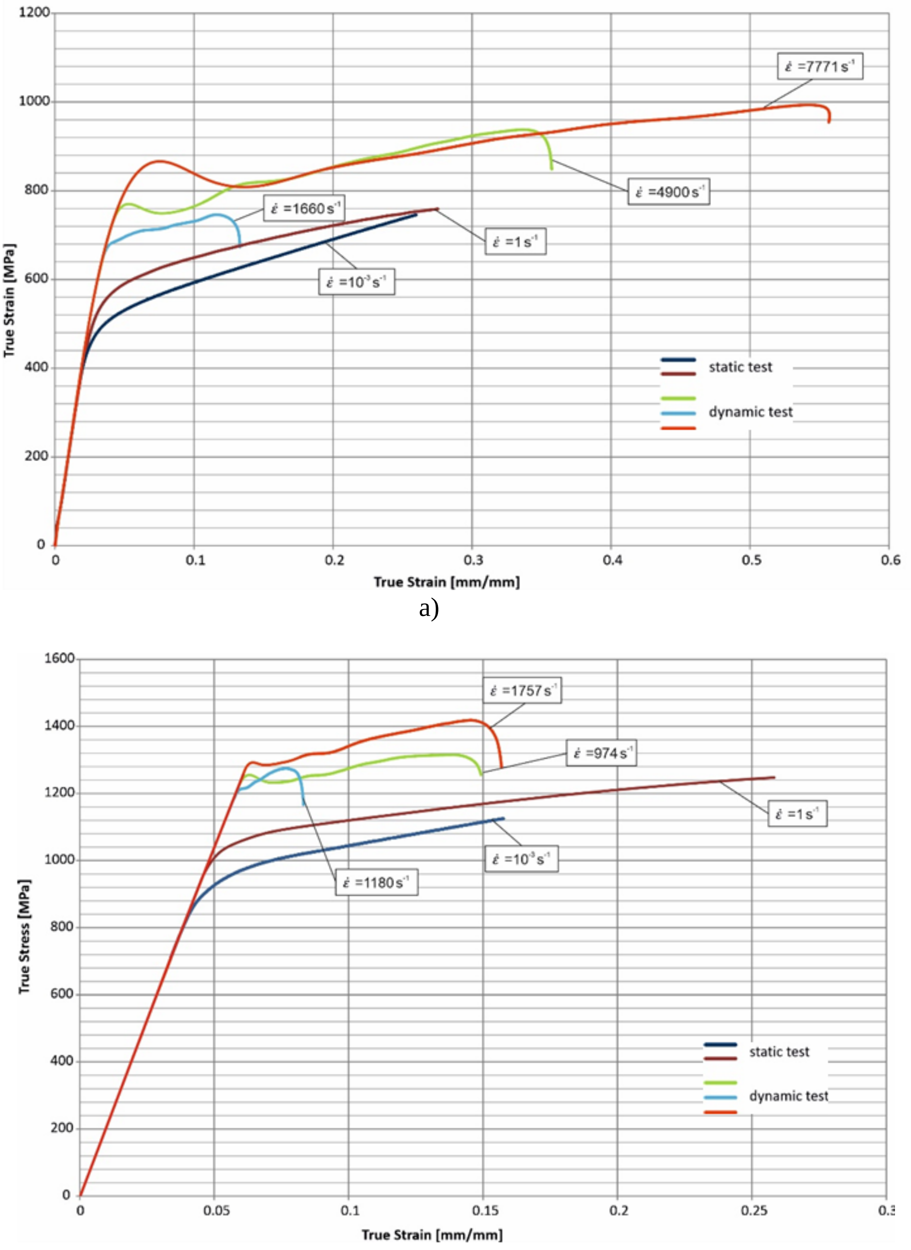
(a) (b)

(c)

Fig. 6. Metallographic structure of: a) metallurgical Ti-6Al-4V alloy, b) Ti-6Al-4V alloy manufactured using powder metallurgy method, c) Ti-6Al-4V alloy performed LENS technology

3.2. Testing of mechanical properties

The family of the stress-strain characteristics in the Ti-6Al-4V alloys made by PM-CIP and LENS are illustrated in Fig. 7a, 7b and 7c. A study of the curves shown in Fig. 7a show a distinct strain strengthening effect which, with the strain increased to 0.3, increased the plastic flow stress of the PM-CIP material from approx. 400 MPa to 900 MPa. A similar strengthening was found in the metallurgical titanium alloy and the LENS titanium alloy, where an increase of strain to 0.15 increased the plastic flow stress from approx. 800 MPa to 1400–1500 MPa. For the metallurgical titanium alloy, there was no distinct effect of strain rate change on the actual stress values. For the PM-CIP and LENS titanium alloys, a relationship between the strain rate change and the actual stress values was found. During the testing of dynamic properties on the LENS titanium alloy, adiabatic shear bands were observed which precede the evolution of cracks, visible on the side surfaces of the test specimen (Fig. 8).


True Strain [MPa]
1200
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
0.6
True Strain [mm/mm]
$\dot{\varepsilon}=7771\,s^{-1}$
$\dot{\varepsilon}=4900\,s^{-1}$
$\dot{\varepsilon}=1660\,s^{-1}$
$\dot{\varepsilon}=1\,s^{-1}$
$\dot{\varepsilon}=10^{-3}\,s^{-1}$
static test
dynamic test
True Stress [MPa]
1600
1400
1200
1000
800
600
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0
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0.25
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True Strain [mm/mm]
$\dot{\varepsilon}=1757\,s^{-1}$
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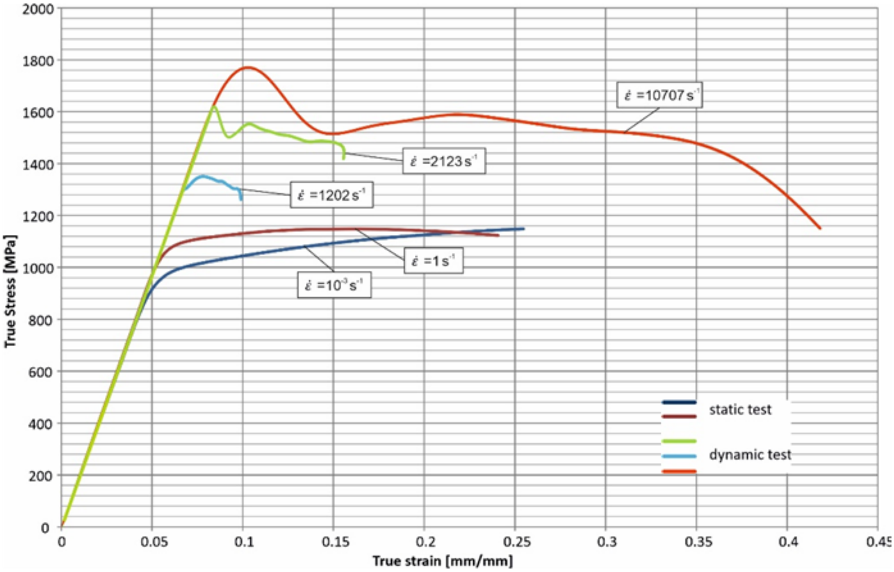
static test
dynamic test

a)

b)



c)

Fig. 7. Stress-strain characteristics of Ti-6Al-4V alloys:
a) manufactured using powder metallurgy method, b) commercial alloy,
c) produced using LENS technology

Fig. 8. Samples with visible adiabatic shear bands

For the sake of comparison, Fig. 9 shows the representative compression curves from all the curves produced by static and dynamic testing. The summary indicates the conclusion that the traditional PM-CIP process can produce a material with mechanical properties much poorer than for commercial Ti-6Al-4V alloy. LENS, however, enables production of a titanium alloy material which outperforms the commercial counterpart in terms of mechanical properties.

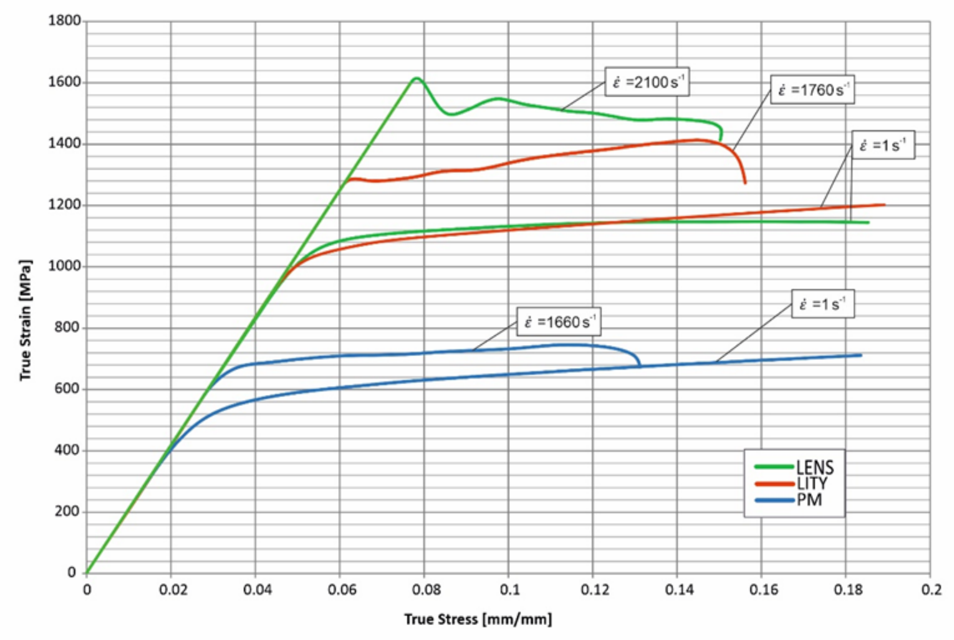


Fig. 9. Set of representative stress-strain characteristics

4. CONCLUSION

The main objective of this paper was to determine the mechanical characteristics of titanium sinters manufactured using different processes. The work was divided into a number of steps to achieve this objective. The analysis of the tested characteristics showed that the materials obtained by traditional PM-CIP and by LENS AM, featured the effect of strain rate change on the actual stress levels. For the dynamic compression tests on the LENS materials, adiabatic shear bands were found. Comparing the sets of curves between each material, the conclusion was made that the LENS material had the best mechanical properties. Laser Engineered Net Shaping (LENS) facilitates the production of materials with very high dynamic mechanical properties for Grade 5 titanium sinters (Ti-6Al-4V).

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Quasi-statyczne i dynamiczne właściwości mechaniczne stopu tytanu Ti-6Al-4V otrzymanego niekonwencjonalnymi technologiami wytwórczymi

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Streszczenie. Celem niniejszej pracy było wyznaczenie właściwości mechanicznych stopu tytanu Ti-6Al-4V wytworzonego metodą klasycznej metalurgii proszków CIP (*ang. Cold Isostatic Pressing*) oraz przy użyciu przyrostowej technologii wytwarzania LENS (*ang. Laser Engineered Net Shaping*). Badaniom poddano także komercyjny stop Ti-6Al-4V jako materiał referencyjny. Próbki do badań wytrzymałościowych przygotowano z wysokiej jakości proszku stopu tytanu gatunku 5. Dla wykonanych próbek materiałowych wyznaczono gęstość, porowatość, a także określono twardość. Ponadto, wyznaczono krzywe ściskania dla badanych materiałów na podstawie rezultatów testów wytrzymałościowych w warunkach statycznego i dynamicznego obciążenia. Wykorzystano do tego celu uniwersalną maszynę wytrzymałościową (*UTS, ang. Universal Testing Machine*) oraz stanowisko dzielonego pręta Hopkinsona (*SHPB, ang. Split Hopkinson Pressure Bar*). Na podstawie otrzymanych wyników badań stwierdzono, iż stop tytanu uzyskany metodą klasycznej metalurgii proszków charakteryzuje się niższymi parametrami wytrzymałościowymi od jego komercyjnego odpowiednika. Próbki wykonane technologią LENS cechują się wyższymi parametrami w porównaniu ze stopem komercyjnym zarówno w statycznych jak również dynamicznych warunkach obciążenia.

Słowa kluczowe: stopy tytanu, dzielony pręt Hopkinsona, LENS, wytwarzanie przyrostowe