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Investigation of laser consolidation process for metal powder by two-color pyrometer and high-speed video camera

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ABSTRACT

This paper deals with the measurement of surface temperature on metal powder during the laser consolidation process with two-color pyrometer. Additionally, the aspect of selective laser sintering (SLS) and selective laser melting (SLM) of metal powder is visualized with high speed video camera. As a result, the surface temperature during the laser irradiation was ranged 1520–1810 °C and the consolidation phenomena was classified according to the melting point of metal powder. The metal powder at the heating process cohered intermittently to the melt pool although the laser beam was continuously irradiated to the powder surface.

1. Introduction

Layered manufacturing technology was presented initially by Kodama as a new rapid prototyping technology to fabricate three-dimensional plastic models [1]. This technique became the common technology for additive manufacturing (AM) to produce prototypes, tools and functional end products with a variety of components, such as polymer, ceramic and metal powder [2]. The development of three-dimensional CAD system also contributed to the commercial uses of the layered manufacturing techniques. Indeed, the use of metal powder in layered manufacturing is especially remarkable because the structures obtained are sufficiently strong for practical application [3]. Laser consolidation of metal powder is classified into several types of mechanism according to the energy density on area irradiated by laser beam [4]. Selective laser sintering (SLS) and selective laser melting (SLM) enable the fabrication of three-dimensional models from the powdered materials by selectively heating and fusing powder particles using a laser beam irradiation.

Problems encountered in SLS and SLM are the accuracy of the structures obtained by the layered manufacturing processes. The dimensional accuracy and the surface quality of the structures are inferior to conventional technologies such as a milling and grinding, and these are important limitations to layered manufacturing technology. The improvement of these problems was proposed symptomatically such as an employment of secondary laser irradiation without depositing a new metal powder layer [5] and an application of the atmospheric plasma spraying system (APS) on the consolidated structure [6]. Additionally, Abe et al. developed a multitasking machine in which a laser consolidation of metal powder and an end milling of the edge of consolidated structure were performed alternately [7].

The principal factor which causes the deformation of the consolidated structure in SLS and SLM is the residual stress, which is induced by the thermal gradient brought on by rapid heating and cooling during layer consolidation. Shiomi et al. measured the distribution of residual stress within the consolidated structure in the SLM process [8]. They reported that the tensile residual stress remaining in the surface layer of the consolidated structure was improved by re-scanning of the laser beam without deposition of new powder. The influence of the thickness of substrate and the height of consolidated structure on the residual stress in the surface layer was also investigated in our previous study [9]. It was shown that the deformation of the consolidated structure was related to the value of residual stress and that residual stress increased with the increase in the number of layers. It is quite difficult to eliminate the residual stress induced inside the consolidated structure although pre-heating of the powder bed is effective in reducing it.

In order to improve the dimensional accuracy causally in layered manufacturing technology, it is essential to monitor and visualize the laser irradiation area during powder consolidation. This research focuses on the measurement of surface temperature of ferrous based metal powder by irradiation with Yb:fiber laser beam. Surface temperature was measured with two-color pyrometer employing an optical fiber with a different acceptable wavelength of InAs and InSb detectors, which were developed by the authors [10]. Additionally, the powder surface during laser irradiation was monitored with high speed video camera in order to clarify the consolidation mechanism.

2. Experimental method

2.1. Two-color pyrometer

A schematic illustration of the two-color pyrometer is shown in Fig. 1 [10]. The pyrometer is composed of an optical fiber, a condenser, an optical filter and two types of infrared detectors;

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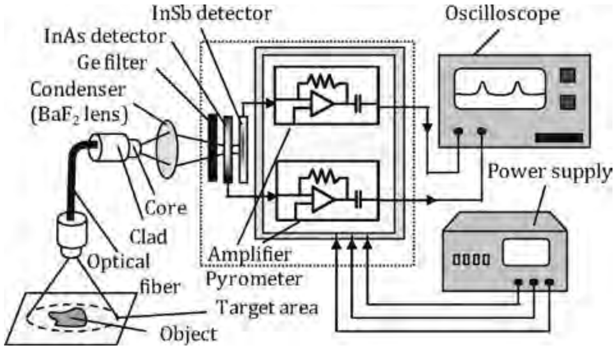

Fig. 1. Fundamental structure of two-color pyrometer.

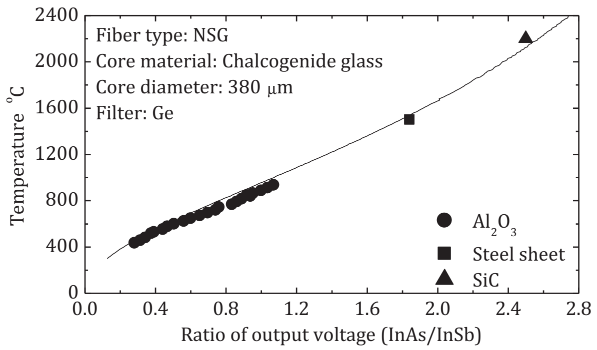

Fig. 2. Calibration curve obtained.

namely, an InAs detector and an InSb detector. These detectors are mounted in a sandwich configuration, with each detector having a different range of acceptable wavelength. The infrared energy radiated from the target is led to the two-color detector through a chalcogenide glass fiber and converted to an electric signal, amplified and stored in a digital memory. The frequency characteristics of the pyrometer are a flat response for sine wave from 10 Hz to 100 kHz, so that the pyrometer has sufficient speed to measure the laser irradiation area [11]. By taking the ratio of output signals, the influence of the emissivity occurring in the surface characteristics at the laser irradiation area is negligible [12]. To protect the two-color detector from laser irradiation, a germanium optical filter with a thickness of 1 mm was applied. This filter cut off nearly all wavelengths below 1600 nm.

The calibration was carried out using two different methods. In the range up to 1000 °C, the known uniform temperature on a radiation surface was measured with a thermocouple. Alumina was used as a target material. In the range exceeding 1000 °C, the minimum output, at which the surface of the specimen melted when the laser beam was irradiated, was measured. As target materials, SiC, with a melting point of 2200 °C, and a steel sheet with a melting point of 1510 °C were used.

Fig. 2 shows the calibration curve obtained by taking the ratio of the output voltages of InAs and InSb detectors. By taking the ratio of output signals, the influence of the emissivity occurring in the surface characteristics at the laser irradiation area is eliminated. The solid line indicates the curve derived from the sensitivity of the parts which compose the two-color pyrometer. The experimental points coincided well with the calculated curve. The interpretation of ratio to temperature was calculated with a solid line. The range of temperature measurement with the two-color pyrometer was 400–2200 °C.

2.2. Experimental setup

The experimental arrangement is schematically illustrated in Fig. 3, and the experimental conditions are summarized in Table 1. This equipment was a self-designed consolidated system composed of laser equipment and consolidation facility of a metal powder. The laser beam used was a continuous Yb:fiber laser (SUNX Ltd.: LP-F10) with a maximum laser power of 40 W. The intensity of relative density of the laser beam radiated from the galvanometer mirror formed a Gaussian shape. The beam diameter at the point where the intensity falls to $1/e^2$ times from the maximum value was 45 μm. The substrate used to consolidate the metal powder was cold rolled steel, and its surface was processed by sandblasting with an average grain size of #46 in order to improve the wetting property of the melted powder. The vessel for the consolidation was filled with nitrogen to prevent the oxidization of the metal powder during laser irradiation.

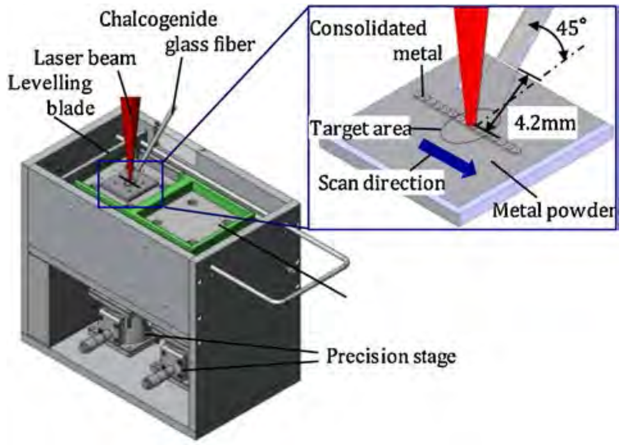

Fig. 3. Experimental setup for temperature measurement.

Table 1
Experimental conditions.

Laser source		
Wavelength	[nm]	1070
Power	[W]	1–40
Beam diameter at focal spot	[μm]	45
Scan speed	[mm/s]	1–88
Substrate		
Material		Cold rolled steel
Thickness	[mm]	3.2
Surface roughness R_a	[μm]	3.5
Metal powder		
Material		Fe, Cu, Ni
Shape		Irregular
Particle mean diameter	[μm]	25
Bulk density on substrate	[kg/m^3]	4200
Absorption ratio of laser beam	[%]	25
Thermal conductivity	[W/m K]	0.14
Layer thickness	[mm]	0.05
High speed video camera		
Recording speed	[fps]	10,000
Resolution		768 × 648
Light source		Metal halide lamp

The metal powder used was a mixture of 70% steel powder, 20% copper phosphorous alloy powder and 10% nickel powder. Each powder was prepared by the gas atomization method. The metal powder was deposited on the substrate using a leveling blade, and its thickness could be controlled by the precision stage at the required thickness.

The surface temperature during line consolidation on the deposited metal powder was measured. The laser beam was irradiated to the powdered surface through a galvanometer mirror at the focus spot, and scanned using programmed NC data. The chalcogenide glass fiber of the two-color pyrometer was set at a distance of 4.2 mm from the laser irradiation area and at an angle of 45° to the powdered surface. The center of the laser irradiation area always passed the center axis of the glass fiber. Hence, the fiber received the infrared rays radiated from the laser irradiation area when the laser beam passed through the target area of the fiber. The acceptance angle of the fiber was 24°. Therefore, the passing length through the target area was 4.1 mm [13]. The influence of the irradiation parameter on surface temperature was investigated.

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Additionally, the consolidation phenomena of metal powder during laser beam irradiation were visualized using a high-speed video camera (Photron Ltd.: FASTCAM SA5) with a maximum recording speed of 100,000 fps. The video camera was set vertically above the powdered surface. A metal halide lamp was used as the light source. The laser beam was then irradiated to its surface at an angle of 45° to the powdered surface. Therefore, the beam diameter on the surface was 45 μm × 64 μm.

3. Results and discussion

3.1. Consolidation mechanism of metal powder

Fig. 4 shows the consolidation aspect in the SLM process of metal powder during laser beam irradiation. The schematic illustrations of powder consolidation in each image are also represented. Here the laser power was set at 40 W whereas the scan speed was 45 mm/s. These images were recorded by the high-speed video camera at a time interval of 4 ms. When the laser beam was irradiated to the powder surface, the powder was heated and the molten area was formed as shown in (a). The circumferential powder of the laser beam spot was also affected by the conducted heat induced by laser beam irradiation, and these powders cohered to the center of the laser beam due to the surface tension of molten powder, as indicated in (b). The cohesion of circumferential metal powder to the molten area occurred intermittently although the laser beam was continuously irradiated to the powder surface. In addition to the surface tension induced by the melting of the metal powder, the shape of the molten powder was strongly influenced by the adhesion force induced by the wetting properties. The laser beam was scanned on the powder surface and the molten area was formed in the laser scan direction, so that the molten spherical powder was growing up gradually, as depicted in (c). When the laser beam passed through the molten area which was sufficiently large due to the surface tension, the molten powder resulted in the solidification represented in (d). The increase of heat capacity induced by the growth of the molten powder also promoted the solidification of the molten powder. In addition to this, newly molten powder was also formed near the solidified powder. These processes were periodically repeated according to the progress of laser beam irradiation.

3.2. Surface temperature during laser beam irradiation

Fig. 5 shows the variation of temperature during laser beam irradiation with the energy density. Here the layer thickness on the substrate was 0.05 mm. The energy density was calculated using laser power, scan speed and beam spot diameter. The typical output signal of InSb detector and temperature history obtained from the two-color pyrometer are also represented in Fig. 5. When the laser beam reached the target area of the pyrometer, the infrared energy was immediately detected by the detector and converted into an electric signal. The output signal increased as the laser beam approached the center of the target area, and reached its maximum value when the laser beam reached the center of the target area. The output signal then decreased gradually after the laser beam passed the center. The variation in temperature obtained taking the ratio of output signals showed similar trends with that of the output signal. The laser beam was not detected in the detector due to the working of a germanium filter.

The temperature on the metal powder was greatly influenced by energy density as shown in Fig. 5. The surface temperature at an energy density of 2.5 J/mm^2 was 1520 °C, and 1810 °C at 10.1 J/mm^2. Fig. 6 compares the image of the consolidated structure to investigate the influence of energy density on metal consolidation. Schematic illustrations of powder consolidation are also shown. Fig. 6(a) shows the energy density at 2.5 J/mm^2 and Fig. 6(b) shows the energy density at 10.1 J/mm^2. When the energy density was 2.5 J/mm^2, the surface temperature was 1520 °C and was lower than the melting point of steel powder. Therefore, the steel powder was partially melted and the shape of the solidified structure was rough. On the other hand, when the energy density was increased to 10.1 J/mm^2, the surface temperature was 1810 °C. The steel powder was fully melted and the shape of the consolidated structure was spherical due to the surface tension. The melting point of the steel powder which was the main component of the powder mixture was

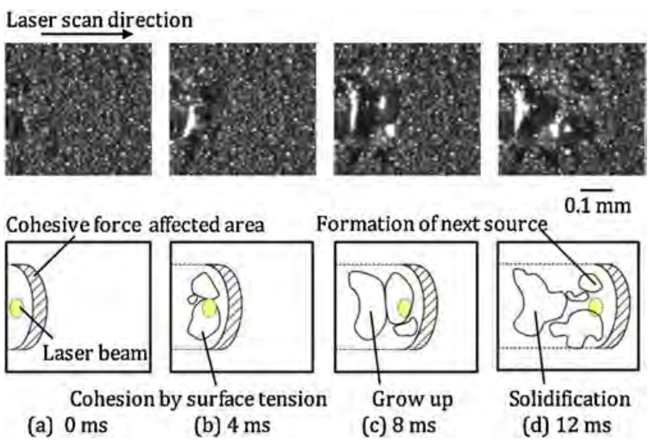

Fig. 4. Consolidation aspect of metal powder.

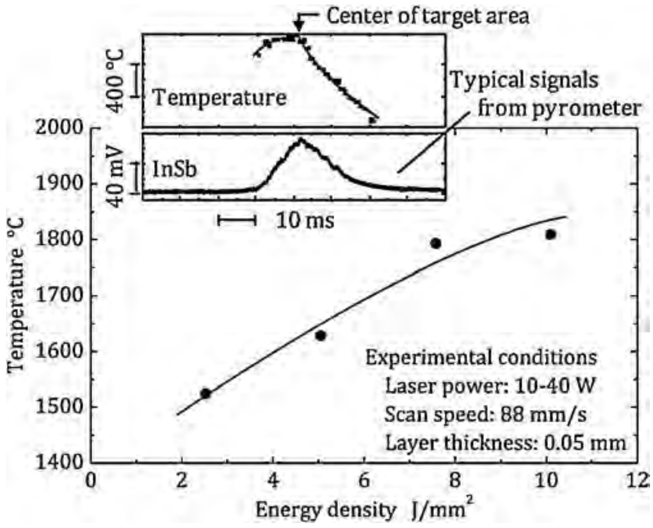

Fig. 5. Variation of temperature with energy density.

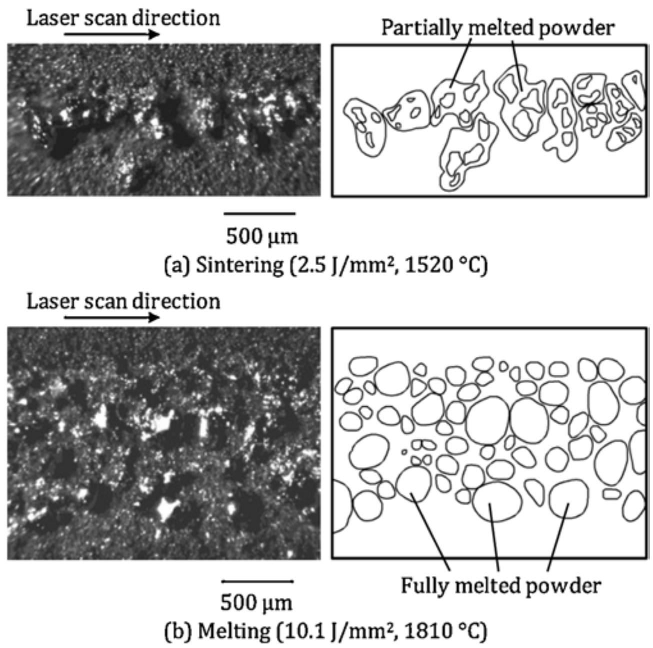

Fig. 6. Comparison of the influence of energy density on consolidation.

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1540 °C, and the melting point of copper and nickel which was included in the powder mixture was lower than that of steel powder. The consolidation phenomena of powder mixture were strongly related to surface temperature. Especially, the melting point of steel powder was important factor to classify the consolidation phenomena of powder mixture. Additionally, it was also shown that consolidation behavior could be controlled by measuring the surface temperature on the powder mixture non-destructively.

3.3. Visualization of the source of residual stress on metal powder

Fig. 7 shows an image and schematic representation of consolidation when the laser power was 40 W and the scan speed of the laser beam was 1 mm/s. During cooling process of the metal powder, the consolidated structure shrunk toward the center of the structure. The shrinkage of consolidated structure started after 250 ms of laser irradiation. It was estimated that the shrinkage of the consolidated structure occurred when the surface temperature was sufficiently low. The shrinkage after solidification of metal powder caused residual stress on the consolidated surface. The source of residual stress on the metal powder was visualized by the observation of powder consolidation during laser beam irradiation.

Fig. 8 shows the variation of the width of molten powder with energy density. Additionally, the difference of width in molten area and consolidated structure in each energy density is also shown in it. Here the width of molten area and consolidated structure were both defined as the width into which all consolidated structures were included inside the double parallel lines with a reference length of 2.6 mm. The width of molten area was significantly larger than that of the spot diameter of the laser beam, and its value was increased with energy density due to the conducted heat induced by laser beam irradiation. On the other hand, the difference of width in molten area and consolidated structure in the process of solidification was almost constant under each condition. The reduced distance was the most important parameter in the generation of the residual stress. Shiomi et al. reported that the residual stress on the consolidated structure was not affected by the laser conditions [8]. It was also shown in our previous paper that the parameter that influenced residual stress was the number of layers in the consolidated structure [9]. Since the generation of residual stress could not be avoided in the process of laser consolidation, it was necessary to perform post process on the consolidated structure to improve residual stress.

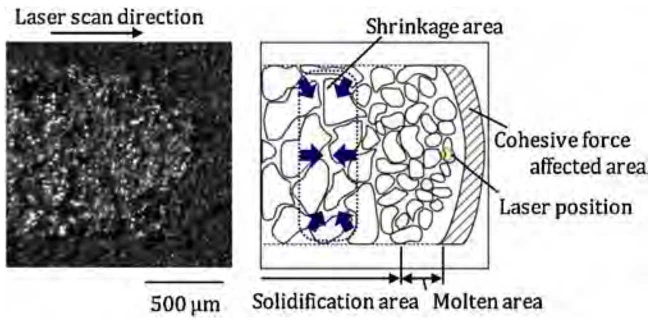

Fig. 7. Consolidation aspect of metal powder.

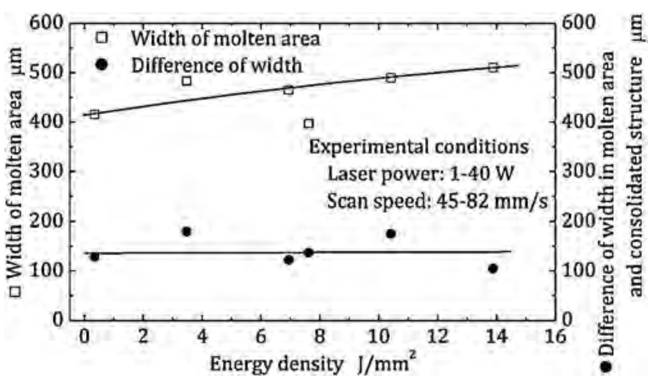

Fig. 8. Variation of molten width and shrunk distance with energy density.

4. Conclusions

In this paper, the surface temperature of the powder mixture in metallic additive manufacturing during laser beam irradiation was measured by two-color pyrometer employing optical fiber, and the aspect of the powder consolidation was monitored by high-speed video camera in order to clarify the consolidation mechanism. Additionally, the influence of energy density on consolidation characteristics was investigated experimentally. The results obtained were as follows:

1. The two-color pyrometer with optical fiber made it possible to measure the surface temperature at the irradiated area of laser beam while the metal powder was consolidated. The measured temperature during the laser irradiation ranged from 1520 °C to 1810 °C.
2. The consolidation phenomena of powder mixture were strongly related to surface temperature, and the possibility of controlling consolidation behavior by measuring the surface temperature was demonstrated.
3. In the solidification process of molten powder, the cohesion of circumferential metal powder to the molten area occurred intermittently although the laser beam was continuously irradiated to the powder surface.
4. The consolidated structure shrunk during cooling process of metal powder, and its shrinkage occurred when the surface temperature was sufficiently low. The source of residual stress on the metal powder was visualized by the observation of powder consolidation during laser beam irradiation.

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References

[1] Kodama H (1981) Automatic Method for Fabricating a Three-dimensional Plastic Model with Photo-hardening Polymer. *Review of Scientific Instruments* 52(10):1770–1773.
[2] Kruth JP (1991) Material Increase Manufacturing by Rapid Prototyping Techniques. *Annals of the CIRP* 40(2):603–614.
[3] Levy GN, Schindel R, Kruth JP (2003) Rapid Manufacturing and Rapid Tooling with Layer Manufacturing (LM) Technologies, State of the Art and Future Perspectives. *Annals of the CIRP* 52(2):589–609.
[4] Kruth JP, Levy G, Klocke F, Childs THC (2007) Consolidation Phenomena in Laser and Powder-Bed Based Layered Manufacturing. *Annals of the CIRP* 56(2):730–759.
[5] Yasa E, Kruth JP, Deckers J (2011) Manufacturing by Combining Selective Laser Melting and Selective Laser Erosion/Laser Re-melting. *Annals of the CIRP* 60(1):263–266.
[6] Zhang B, Zhu L, Liao H, Coddet C (2012) Improvement of Surface Properties of SLM Parts by Atmospheric Plasma Spraying Coating. *Applied Surface Science* 263:777–782.
[7] Abe S, Higashi Y, Fuwa I, Yoshida N, Yoneyama T (2006) Milling-Combined Laser Metal Sintering System and Production of Injection Molds with Sophisticated Functions. *ICPE2006, 11th International Conference of Precision and Engineering*, 16–18 August, Tokyo, Japan, 288–293.
[8] Shiomi M, Osakada K, Nakamura K, Yamashita T, Abe F (2004) Residual Stress within Metallic Model Made by Selective Laser Melting Process. *Annals of the CIRP* 53(1):195–198.
[9] Furumoto T, Ueda T, Aziz MSA, Hosokawa A, Tanaka R (2010) Study on Reduction of Residual Stress Induced during Rapid Tooling Process, Influence of Heating Conditions on Residual Stress. *Key Engineering Materials* 447–448:785–789.
[10] Ueda T, Sentoku E, Yamada K, Hosokawa A (2005) Temperature Measurement in Laser Forming of Sheet Metal. *Annals of the CIRP* 46(1):117–122.
[11] Ueda T, Hosokawa A, Oda K, Yamada K (2001) Temperature of Flank Face of Cutting Tool in High Speed Milling. *Annals of the CIRP* 50(1):37–40.
[12] Davies MA, Ueda T, M'Saoubi R, Mullany B, Cooke AL (2007) On the Measurement of Temperature in Material Removal Processes. *Annals of the CIRP* 56(2):581–604.
[13] Ueda T, Yamada K, Nakayama K (1997) Temperature of Work Materials Irradiated with CO_2 Laser. *Annals of the CIRP* 46(1):117–122.

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