IRAQI JOURNAL OF MATERIALS
Volume (4) Issue (1) January-March 2025, pp. 43-48

Influence of Processing Pattern on Topographical Characteristics of Metal Microstructures Fabricated by Pulsed Laser Machining

Oday A. Hammadi

Department of Physics, College of Education, Al-Iraqia University, Baghdad, IRAQ

Abstract
In this paper, pulsed Nd:YAG laser of 60kW peak power was used to carry out material removal process to manufacture 3D microstructures from Inconel-600 samples at micrometer dimensions for micro-stamping and micro-embossing on metals. Different parameters, such as power density, overlap of laser pulses and processing velocity, were determined to introduce their effects on the roughness of the machined surfaces. The surface roughness was decreased by 80% to reach about 1 micron as the velocity of laser beam was increased by 600% to be 300 mm/s.

Keywords: Laser-assisted manufacturing; Material removal; #D microstructure, Inconel alloys
Received: 20 August 2024; **Revised:** 22 October 2024; **Accepted:** 29 October; **Published:** 1 January 2025

1. Introduction

Laser removal of metallic samples has many features and advantages when compared to other methods and techniques of material removal [1-3]. These features still not competed especially in production of microstructures and nanostructures for ultra-fine applications [4-8]. The interest in microstructures with 3D geometries has dramatically increased in microsystems applications in recent years. To promote the wide applications of such 3D microstructures, the materials and patterning technologies for their fabrication should be inexpensive [9-12]. Material processing with lasers is an expanding field since it not only makes manufacturing cheaper, faster, cleaner, and more accurate but also opens up entirely new technologies and manufacturing methods that are simply not available using standard techniques [13-17].

The production landscape of industrial manufacturing is expected to undergo significant change with the increasing adoption of additive manufacturing (AM) technology [1–4]. This AM technology offers potential benefits for a wide range of industries, including defence, biomedical, aerospace, jewellery making, automotive, construction, electronics, food, and healthcare [2–6]. The use of a laser sources, both continuous wave (CW) lasers and long-pulsed lasers, to heat and melt materials is common in most AM processes [7] CW lasers are typically used for larger parts, while pulsed lasers are preferred for thin, finely structured and precision parts [8]. Some key process variables such as layer thickness, laser intensity, hatch spacing, light absorptance, scanning speed, and laser energy density will impact the overall quality of components in laser-based AM [9–12], but several challenging issues remain in the adoption of this technology. For example, the accuracy of existing laser-based AM is limited by fundamental variables such as powder size and laser spot size, which are crucial in manufacturing of micro-features with high accuracy [13]. Processing of high-melting- point or high-reflectivity materials is also challenging because of the thermal properties of these materials in spite of development of different lasers at various wavelengths [13–15]. The use of a combination of materials, including metals, ceramics, glass, and alloys, for fabricating composites are desirable, but the mismatch of materials with different cooling rates or thermal expansion coefficient causes a variety of problems during production, including the peeling of different layers and formation and distribution of crystal defects [13–15]. Heat-affected zones resulting from heat accumulation degrade the mechanical properties of materials by creating residual stresses, porous structures, and micro-cracks. These factors together with not-yet-great surface finishing, productivity, quality control, reliability, product dimensionality, and a narrow choice of printable materials are significant additional issues that need to be addressed [13]. However, the advent of ultra-short pulse lasers, including picosecond (ps) and femtosecond (fs) lasers, presents a significant opportunity to extend the range of materials used in AM technology [14], because of their three specific characteristics: a broad spectral bandwidth, ultra-short pulse time and the ability to generate extremely high power intensities in the range of 10^{13}–10^{14} W/cm^2 [16,17].

Efficiency of laser sources depends on basic physical processes involved in laser micromachining (LMM). The most critical laser parameter is often the laser pulse duration [18-21]. For efficient material removal with minimal heat affected zone shorter pulses are preferable because energy concentration in time prevents heat diffusion into surrounding area thus reducing heat-affected zone (HAZ) [22,23]. Also, higher peak power initiates high-degree non-linear mechanisms, including direct multi-photon ionisation even in transparent materials. Finally, applying laser energy over a relatively long time results in distortion of machined micro features [24,25].

With the recent progress of micro-electro-mechanical systems (MEMS), interest in the fabrication of microstructures using different methods and materials is increasing. Although silicon is mostly preferred to other materials because of the well-established semiconductor manufacturing processes, metallic structures can provide other advantages such as higher strength and flexibility [26-28]. Titanium and Inconel are excellent materials exhibiting high corrosion resistance, strength-to-weight ratio, low modulus of elasticity. Furthermore, they are biocompatible materials employed for medical implants. Biomedical microdevices, microgripper or sensors are required to meet the biocompatibility and safety considerations if installation in living body is considered [29-31].

Fabrication of metallic microstructures may be done by precision machining, electro discharge machining, laser machining, etc. Laser machining is a promising technique because it is a noncontact simple process with relatively small hardware requirement [32,33]. Direct laser machining, however, has drawbacks due to high thermal load that may lead to thermal deformation of microstructures or poor surface quality by melting and droplet formation [34]. The material removal is related to the total absorbed energy, and it is the mechanical behavior which is most complicated, involving particle trajectories and flow of both liquids and solids [35].

Requiring fast and flexible methods to manufacture microstructures and parts at decreased costs, needs for micro-tools have increased in too special way [13]. The needed microstructures have some requirements must be satisfied such as very small dimensions (<100μm), high aspect ratio (>1:20) and too small roughness of surfaces (<1μm). As the tools used for stamping, embossing, injection molding and other similar applications must be made of hard metals as they should be weariless [36]. The electric discharge machining can be considered as an available alternative, but the costs of microstructured electrodes are high [37].

This problem can be solved by using Nd:YAG laser removal for microstructures. The advantages of laser micromachining include small heat affected zone (HAZ), control over machining depth, rapid throughout and accomplishment of machining at any time during or after processing [38]. Using a pulsed Nd:YAG laser, 6□m-wide grooves were cut in a 300nm thick gold layer coated on sapphire and 2.5□m-wide grooves could be cut in a 200nm thick layer of nichrome on quartz. Lines of 1μm in wide were scribed in tantalum nitride, titanium and nichrome films. Scribing speeds were less than about 2mm/sec and were limited by the 400Hz-pulse repetition rate frequency [39].

The Nd:YAG laser is employed in a direct writing method with radiation and hard metals can be structured with Nd:YAG laser method since it has no material restrictions. Additionally, the development of high-quality diode-pumped Nd:YAG lasers opened new fields in machining with higher harmonic generation, high beam quality, short laser pulse and high precision positioning tables. All these mentioned specifications improve the quality of microstructures produced by laser-employed methods [40]. The process efficiency is determined by the choice of laser source itself, as well as by the system technology such as optical elements for beam shaping and guidance of workpiece handling. Beside the system technology, the choice of an appropriate laser and handling system ensures an efficient processing and repair of microelectronic components [41,42]. Usually, production of micro-parts and micro-tools by Nd:YAG laser removal requires so low technical effort to be achieved.

2. Experiment

An important parameter for the laser beam removal with a pulsed Nd:YAG laser is the overlap of laser pulses. This parameter determines the average depth of removal per laser pulse, which can be higher than the depth of a single laser pulse, and the quality of the worked surface. Subsequent overlapping laser-pulses deposit some of the newly ejected material back into previously machined cavities. The nature of the resultant kerf depends on the percentage overlap and the aspect (depth-to-width) ratio of the kerf. In Fig. (1), the relation between the overlap and the single laser pulses is shown. The definition of the overlap (*O*) is [43]:

$$O = \left(1 - \frac{m}{d_w}\right) \times 100\% \qquad (1)$$

where m is movement of the axis between two laser pulses, and d_w is effecting working diameter of the laser beam.

Experiments show that with overlap of less than 60%, the kerf remains clean and material flow is small. For larger overlap, the kerf is substantially closed by resolidified material [44]. The effecting working diameter (d_w) needs not to be equal to the focus diameter. Definition of the focus diameter does not depend on the maximum of the power density of the laser beam, but on the power density distribution [45].

A criterion for the quality of a microstructure is the roughness and the structure of the machined surface. For this reason Inconel species was examined, which is used for stamping and embossing tools.

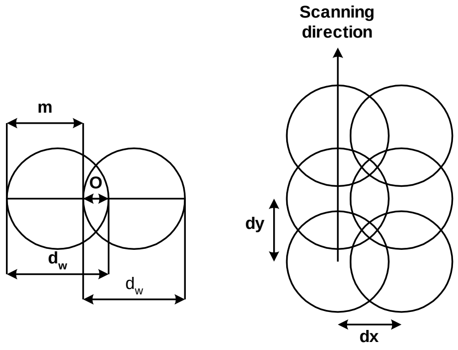


Fig. (1) Overlap principle of laser pulses

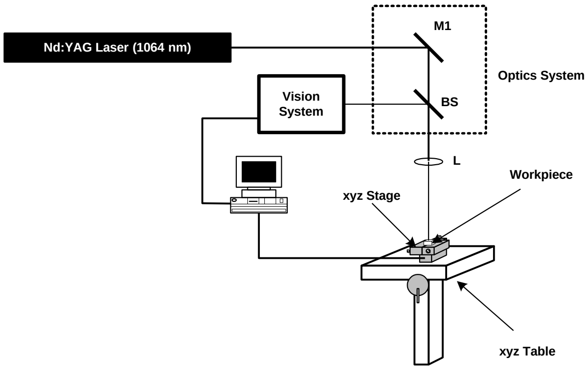
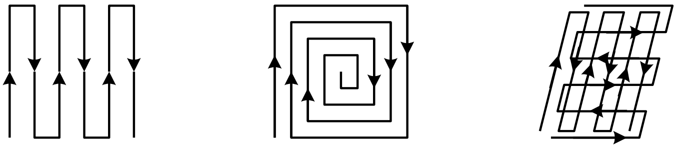


Fig. (2) Experimental set-up used in this work

The laser system is a 300μs duration Nd:YAG laser operating at 1064nm and the Gaussian mode (TEM_{00}), a high-energy stability and a beam divergence of about 1.5mrad. The focus diameter is 50μm with a quartz lens of 2.54cm focal length. The peak power obtained is about 60kW and average power delivered is 10W at 1064nm. Samples processed are 2cm-thickness Inconel-600. Mechanical and physical properties of this alloy are characterized by 225Hv hardness, 1665K melting temperature and $7.1\text{x}10^{-6}$m^2/s thermal diffusivity at 273K.

Manual moving table was used for the coarse movement as the technique used in this work requires too precise positioning, so, a computerized step-motor *xyz*-positioning stage was used onto the manual table for fine movement. A QuickBasic 3.0 software was used for controlling the motion of the xyz-stage, which has high dynamic and precise linear drivers. The resolution of the position is 1μm, the positioning accuracy is 10μm and the maximum velocity (sample velocity) is 50mm/s. Laser beam was guided to the focusing lens (L) by mirror (M1) through the beam splitter (BS), as shown in Fig. (2). The beam splitter was used to feed the vision system (camera) accessorized with laser system. The focusing lens was connected with the *z*-axis, while the workpiece was fixed on the *x*-axis and *y*-axis. The position of the focus of laser beam relative to the workpiece can be adjusted with the *z*-axis.

Laser-material processing techniques are mostly computer-aided and the computer software used in this work was developed for laser removal application. The computer-aided laser material-removal process is divided into three steps: design, slicing and postprocessing [46] and this process can be achieved in one of three modes: scanning, vector or modified-scanning mode, as shown in Fig. (3).



1. Scanning mode

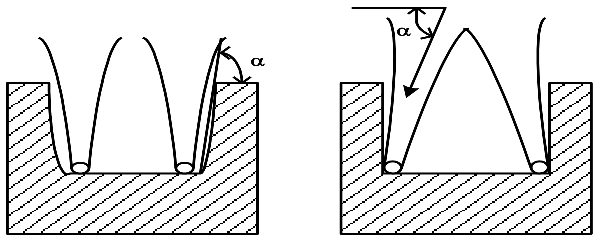
2. Vector mode

3. Modified scanning mode

Fig. (3) Net shapes of material removal process

3. Results and Discussion

The net shape of material removal for several slices influences the result. It is possible to change the direction after each slice (modified scanning mode) to get a homogeneous surface with low roughness. As with most optical manufacturing methods, there is a problem to produce vertical walls explained in Fig. (4). The removal can be controlled to generate vertical walls by titling the specimen relative to the incident laser beam. It is possible to tilt the specimen in case of a basic geometry, but in case of complicated geometries it is recommended to use a special titling device for the laser beam to obtain higher dynamic and accuracy.



without correction of the angle α

with correction of the angle α

Fig. (4) The correction of the angle θ

The effecting working diameter varies throughout changing the peak of power density of laser beam, possibly, because the material has a threshold for laser power density required for material removal, as shown in Fig. (5) [47]. During first half of pulse duration, material absorbs energy reaching its melting point. Material is melted to a distance (melting depth) depending on its thermal diffusivity and interaction time. Second half of pulse duration transfers more energy to the molten leading to vaporization due to easy absorption of energy by the liquid-phase pool. The material can be removed without residue since the ratio of vaporized to melted material is high due to short laser pulse duration.

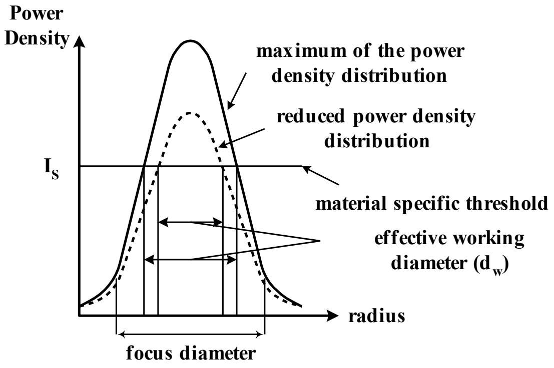


Fig. (5) Difference between focus diameter and effecting working diameter

At an overlap of 0%, the average depth of removal per laser pulse is equal to the removal depth of a single laser pulse. The average removal depth per laser pulse, hence the thickness of a single slice, increases as the overlap increases. As a single laser-pulse is melting its incidence-position, then when overlap is high, a part of processed region will receive much more energy. As a result, removal depth increases. However, too higher overlap may cause thermal damage to the material since more overlap means higher power density, i.e., more thermal effect on same localized area. Thermal effect has induced changes in the properties of processed region since most mechanical and physical properties of metals are temperature-dependent. Figure (6) shows an SEM image of a hole drilled in the surface of Inconel-600 sample with 100 µm diameter.

Figure (7) shows variation of the roughness (R_a) of the surface machined as a function to the overlap of laser pulses in *x*- and *y*-direction. Roughness increases because the increasing overlap has concentrated laser power on the overlapping region.

Liquid-phase molten moves toward expanding direction due to thermodynamics of fluids. As it starts to resolidify, non-uniform distribution of mass results. Depth of removal material increases as power density does, hence surface will be distorted more than before which means more roughness as in Fig. (8).

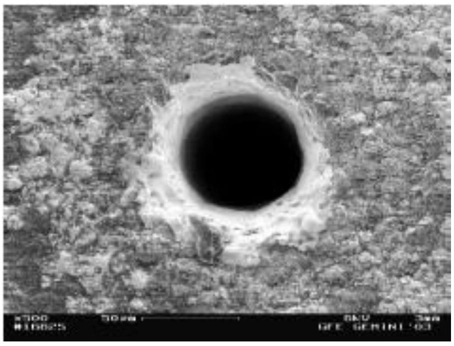


Fig. (6) SEM image of a hole drilled in the surface of Inconel-600 sample with 100 μm diameter

As can be seen from Fig. (9), roughness decreases with increasing velocity of laser beam. The surface roughness was decreased from 1.2 to reach about 1 μm as the velocity of laser beam was increased from 50 to 300 mm/s, respectively. A compensation to laser-beam velocity should be satisfied. Low velocity allows energy per unit area to accumulate leading to higher power density. High velocity prevents pulses to overlap and reduces power received by processed region. As a result, reduced roughness would be achieved.

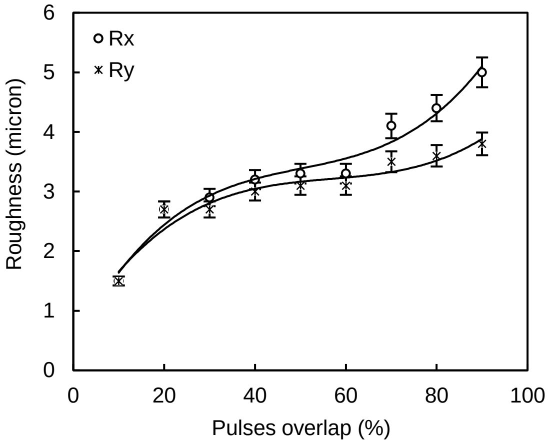


Fig. (7) Variation of roughness (R_a) versus overlap of laser pulses in *x*-direction (R_x) and in *y*-direction (R_y) for machined surface

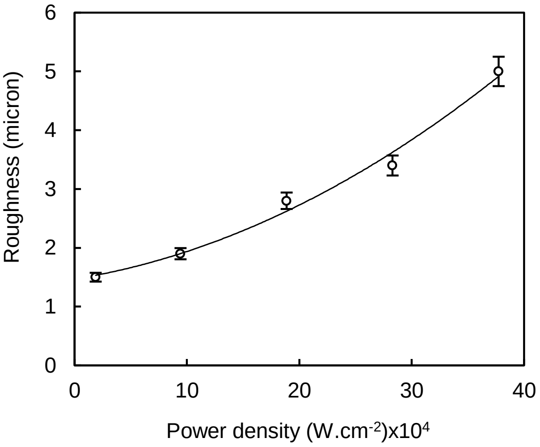


Fig. (8) Variation of roughness (R_a) versus laser power density

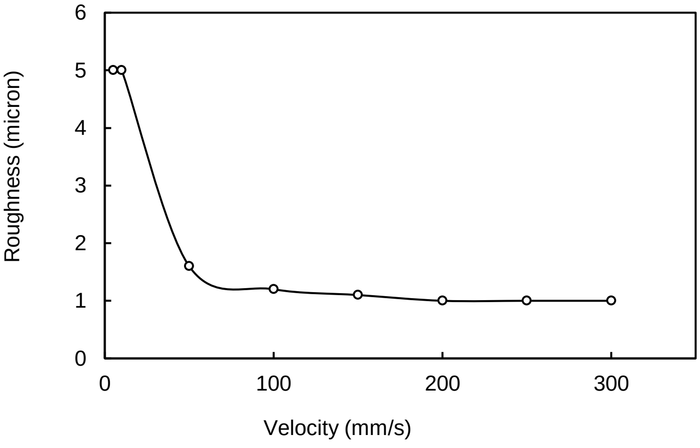


Fig. (9) Variation of roughness (R_a) versus velocity of laser beam

4. Conclusion

Forming microstructures with Nd:YAG laser expands the range of manufacturing techniques for the production of micro-tools. The main advantages of this technology are the variety of materials, flexibility and short cycle from the control software to the machining system. This technology can reduce manufacturing costs of micro-parts. Roughness can be decreased as the overlap of laser pulses decreases and it is recommended to work at the optimum value of overlap that permits to obtain optimum removal depth, hence optimum thickness of a single slice. The basic and complex shapes are possible to produce micro-tools for stamping and embossing of metal parts.

References

[1] J. Dutta Majumdar and I. Manna, “Laser Material Processing”, *Sadhana*, 28 (3-4) (2003) 495-562.
[2] R. Lawes, A. Holmes and F. Goodall, *Microsystem Technol.*, 3 (1996) 17-19.
[3] W. Juan and S. Pang, *J. Vac. Sci. Technol. B*, 12(1) (1994) 422-426.
[4] M. Cohen, R. Kaplan and E. Arthurs, *Proc. IEEE,* 70(6) (1982) 545-554.
[5] Gillner, *Proc. of the MicroEngineering’96*, Stuttgart (1996) 51-55.
[6] L. Migliore, “**Laser Materials Processing**”, Marcel Dekker (NY) (1996) 141-142.
[7] W.W. Duley, “**CO_2 Lasers, Effects and Applications**”, Academic Press (NY), (1976) 273.
[8] N. Tabata, S. Yagi and M. Hishii, *J. Mater. Process. Tech.,* 62(4) (1996) 309-314.
[9] H. Tonshoff et al., *Proc. SPIE,* 229 (1997) 183-193.
[10] R. Jandeleit et al. *J. Appl. Phys.,* A36 (1996) 117-121.
[11] P. E. Dyer, S. M. Maswadi and C. D. Walton, *Appl. Phys. A-Mater. Sci. Process.*, 76, 817-822 (2003).
[12] P. E. Dyer and C. D. Walton, *Appl. Phys. A-Mater. Sci. Process.*, 79, 721-727 (2004).
[13] M. Henyk, F. Costache and J. Reif, *Appl. Surf. Sci.*, 186, 381-384 (2002).
[14] R. Böhme, A. Braun and K. Zimmer, *Appl. Surf. Sci.*, 186, 276-281 (2002).
[15] R. Böhme, J. Zajadacz, K. Zimmer and B. Rauschenbach, *Appl. Phys. A-Mater. Sci. Process.*, 80, 433-438 (2005).
[16] K. Zimmer, R. Böhme and B. Rauschenbach, *Appl. Phys. A-Mater. Sci. Process.*, 79, 1883-1885 (2004).
[17] C. Vass, T. Smausz and B. Hopp, *J. Phys. D: Appl. Phys.*, 37, 2449-2454 (2004).
[18] Y. Kawaguchi, X. Ding, A. Narazaki, T. Sato and H. Niino, *Appl. Phys. A-Mater. Sci. Process.*, 80, 275-281 (2005).
[19] M. Hauer, D. J. Funk, T. Lippert and A. Wokaun, *Optics and Laser Engineering*, 43, 545-556 (2005).
[20] H. Niino, Y. Kawaguchi, T. Sato, A. Narazaki, T. Gumpenberger and R. Kurosaki: *J. Laser Micro/Nanoengineering*, JLMN 1, 38-42 (2006).
[21] S P Harimkar, A N Samant, A A Khangar, Narendra B Dahotre, *J. Phys. D: Appl. Phys.*, 39 (2006) 1642-1649.
[22] Anoop N. Samant, Narendra B. Dahotre, *physica status solidi, Rapid Res. Lett.*, September 2006.
[23] A.-M. Reinecke et al., Nuclear Engineering and Technology, 55(11) (2023) 4159-4166.
[24] C. Perrière et al., Optical Materials: X, 12 (2021) 100107.
[25] S.-I. Nakashiba et al., Physics Procedia, 39 (2012) 577-584.
[26] V.A. Ventrella, J.R. Berretta, and W. de Rossi, Physics Procedia, 39 (2012) 569-576.
[27] K. Zhan, Y. Luo, and Y. Zeng, Chinese Journal of Plastic and Reconstructive Surgery, 4(3) (2022) 140-143.
[28] R.J. Mathew et al., Next Materials, 6 (2025) 100431.
[29] C. Dumitrache et al., Results in Physics, 42 (2022) 105958.
[30] A.B. Pereira et al., Procedia Manufacturing, 41 (2019) 1001-1008.
[31] B.A. Reeves et al., Cell Reports Physical Science, 4(6) (2023) 101449.
[32] O.-V. Grigore and N. Pavel, Results in Engineering, 24 (2024) 103358.
[33] V.A. Ventrella, J.R. Berretta, and W. de Rossi, Physics Procedia, 12(B) (2011) 347-354.
[34] N. Ahmadi et al., Journal of Materials Research and Technology, 27 (2023) 2459-2474.
[35] M.R. Maina et al., Journal of Materials Processing Technology, 299 (2022) 117388.
[36] Y. Nakamura et al., Acta Astronautica, 223 (2024) 426-434.
[37] P. Kumar and A.N. Sinha, Procedia Computer Science, 133 (2018) 733-739.
[38] N. Contuzzi and G. Casalino, Optik, 284 (2023) 170937.
[39] H. Jang et al., Optics & Laser Technology, 167 (2023) 109670.
[40] F.R.U. Cortes et al., Applied Surface Science, 665 (2024) 160326.
[41] M. Bogdanovich et al., Results in Optics, 3 (2021) 100077.
[42] L.-F. Wu and M.-J. Tsai, Optics & Laser Technology, 149 (2022) 107827.
[43] N.H. Abdul Razak et al., Results in Physics, 48 (2023) 106435.
[44] X. Xue, X. Wu, and J. Liao, Chinese Journal of Aeronautics, 34(4) (2021) 375-386.
[45] M. Soleimani et al., Journal of Manufacturing Processes, 131 (2024) 2133-2163.
[46] M. Taheri et al., Journal of Materials Research and Technology, 15 (2021) 5635-5649.
[47] A. Rasouli and H. Naffakh-Moosavy, Journal of Materials Research and Technology, 23 (2023) 6065-6074.