UDC 621.9.08 **doi: 10.20998/2078-7405.2023.99.06**

LASER MEASUREMENTS IN CUTTING PROCESSES

Miklós **Béres** [0000-0002-0185-5321], Gyula **Varga** [0000-0002-1956-790X]

University of Miskolc, 3515, Miskolc - Egyetemváros, Hungary
mechbere@uni-miskolc.hu

Received: 08 November 2023 / Revised:15 November 2023 / Accepted: 20 November 2023 / Published: 01 December 2023

Abstract. *Laser measurements are used chiefly for experiments during metal cutting. The recent development of laser technology offers chances that are advisable to take advantage of machine manufacturing. This article presents some measuring applications for metal cutting. Its purpose is to show separate literature on each technology to provide insight into the possibilities of laser measurements.*
Keywords*: metal cutting; laser measurement; in-process monitoring; LDV; optical sensors.*

1. INTRODUCTION

In production systems, the maintenance of efficient productivity plays a prominent role. The technological processes in machine manufacturing technology have become more diverse in recent decades, and countless new procedures appear every day (Research and Markets [1–5]).

Zaghal and Benke [6] report on determining reliable area sizes for 3D roughness measurement in their work. In their article, Zhou, J., et al. [7] and Zhou, H., et al. [8] analyse in detail the activities related to laser polishing. Lavrinenko et al. [9] present a review study entitled “Modern Developments Related to the Directed Impact on the Cutting Surface of a Diamond Abrasive Tool and its Contact Zone in the Processes of Machining (review)". In their article, they examine in detail the activity of laser sharpening evaluation on diamond wheels [10–11], and also analyse the laser surface roughness measurement [12].

The driving force behind the increase in indicators is reducing production time. At the same time, this phenomenon also affects traditional technological processes. These production processes must also meet quality, reliability and increased productivity [13–14]. Increasing the machining speed is a promising way to speed up the different production steps. However, it also raises new problems. In-situ metrology in production systems improves accuracy and reduces machining time by eliminating repositioning and setting operations [15]. Various monitoring methods and techniques help to achieve these goals. These procedures are increasingly crucial in individual production technology operations [16]. This article does not intend to deal with the various monitoring techniques. However, we must note that the respective areas are slowly separating. Some condition monitoring procedures monitor the machine tool (MCM), while others focus directly on the tool. The former mainly focuses on condition-based maintenance (CBM) [17–20], providing data that can complement a risk-based maintenance strategy (RBM) (offering a severe economic advantage for users). Other monitoring techniques maximise the valuable working time spent on quality production by examining the tool condition. [21–23]. Predictive maintenance uses analytical models to analyse data from sensors that estimate the condition of a part, machine or process. Predictive maintenance procedures benefit from machine data collection and more frequent sampling, while condition-based monitoring applications benefit from multiple sensing inputs [24–25]. At the same time, the condition-based inspection often acts as an early warning system. In parallel with the systems that monitor the tool's condition, we can observe the material separation process separately. This third control strategy is closely related to the previous controls [11], [14].

Today, we have many different sensors and measurement methods at our disposal. However, each has limitations, so the measurement is still burdened with errors [26–27]. The more sensitive the measurement method (for example, laser) is to the physical signal, the more accurately it can reproduce the phenomenon under investigation. From this point of view, they, therefore, offer a definite advantage [28]. At the same time, they may require complicated installation, their area of use may be limited, or their investment costs may be high, so they have not become widespread [29-30]. It can be said for almost all optical sensors, the only exception perhaps being the use of CCD detectors [31]. Using a laser as a measuring tool was still considered expensive almost a decade ago. Today, however, the situation has changed.

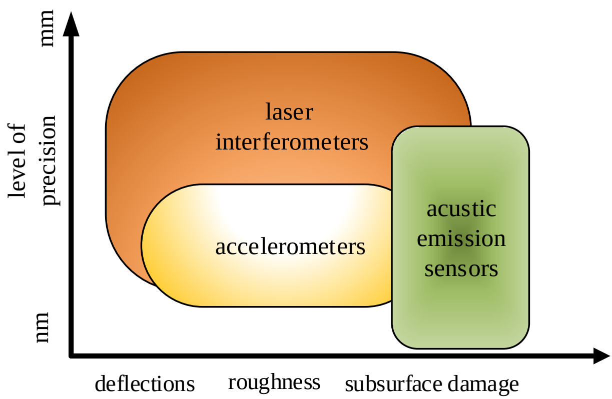

Figure 1. Applicability of laser interferometers compared to accelerometers and acoustic emission sensors

The laser as a measuring device was a costly procedure nearly a decade ago [32]. However, due to the significant reduction in production costs and their intensive use in the electronics industry, their scope of application has widened. Laser devices are still developing at a tremendous pace today. This trend applies to lasers, high-resolution cameras, smart devices, and microcontrollers performing local computing tasks [33]. New application areas come to the fore through the miniaturisation and embedding of measuring devices.

An example of such a device is the multi-beam, integrated semiconductor laser developed by Li et al. [34]. Compared to previous devices, this new six-beam laser chip reduces the loss caused by detection time and increases signal stability. Li's development is beneficial for measuring vibrations in the low-frequency range, with an amplitude of up to a few 100 μm/s, a resolution and quality similar to commercially available LDVs. Subprocesses of the cutting cycle and events that occur (even unexpectedly) require additional attention, as they sensitively affect the accurate evaluation of the measurements. In the case of laser measurements, it happened, for example, that the displacement signal was sometimes "lost" (drop-out) in the transition phase of the cutting cycle [35–36]. In the case of measurements carried out with a Laser Doppler Vibrometer, the reflected signal may become low in intensity and fall below the acceptable level. As a result, the measurement signal itself disappears or becomes non-processable.

The shape of the tool is also an influencing factor. If it gets in the way of the laser, it causes a (sometimes significant) abnormality in the reflected signal. Such a phenomenon can be experienced, for example, in drilling [36].

The mentioned reasons partly explain the common practice that laser measuring devices are usually not used alone but together with other sensors [35], [37–41]. At the same time, laser devices may be required as an additional signal source or to clarify the dynamic model of the system. This is especially true during cutting.

Figure 1. (based on [42]) provides some information about the applicability of laser interferometers used in ultra-precision machining as a function of accuracy and control parameters.

2. LASER MEASUREMENTS IN TURNING

Turning is often the subject of investigation as a traditional machining process. Many proven measurement methods have been developed for its study. However, the power consumption calculated based on the current consumption of the main spindle is used as the input parameter that forms the basis of condition monitoring. The power consumption strategy is used primarily in performance-based TCM (Tool Condition Monitoring) to identify the end-of-life condition of a tool. The disadvantage at the same time is that it is less suitable for effectively detecting tool breakage and other similar sudden events [43].

In the case of turning, more superficial measurements are made with the help of a laser. Its early consumption, which is still present today, is the tachometer. First, its implementation is simple, so we can even measure the signal taken from the chuck with it. Urbikain and his colleagues also used the laser this way when they carried out measurements on a CNC lathe centre, investigating the practical implementation possibilities of the SSV (spindle speed variation technique) [44]. In the experiments, the measurement of energy consumption ensured the balance between better stability limits and acceptable spindle behaviour. Accurate speed data was required for feedback. This data was provided by the laser - successfully.

We should mention its other use as a surface scanning method. A procedure used not only for turning but also for other cutting operations. A procedure used to check both the tool and the machined surface. In their recently published article, Ádám Kiss and his colleagues looked for answers to the causes of self-excited vibrations during turning [45]. They obtained the dynamic behaviour of the vibrations generated during the machining process by comparing the results from the measurement of the roughness of the machined surface with the theoretical correlations. For this purpose, an industrial laser differential displacement meter was used to measure the deviation of the surface from the ideal geometry. In the case of most surfaces, the ratio of regular reflection and diffuse reflection is a function of surface roughness. Therefore, the reflected light pattern carries information about the quality of the surface. During their measurements, the sensor provided sufficient accuracy for detection. As a limitation, the laser spot is not an ideal point but an ellipse. Since the sensor measures the average of the surface roughness - moreover, not symmetrically - this effect appears as a moving average along the measurement line. Spot asymmetry is often encountered when the instrument uses a semiconductor laser. In such a case, the measurement distance must be considered. In the case of spatial-mode semiconductor solid-state lasers (SD), the semiconductor laser beam, at a suitable distance both in the direction perpendicular to the active layer and parallel to it, can only seem Gaussian [46] or Lorenz distributed [47]. Therefore, the measurement distance is always problematic for these measurements - due to the type of laser.

A similar laser application was included earlier in a series of experiments by Wong and his research group [48]. In their article, they presented an optical method that uses the scattering pattern of reflected laser light to track the condition of the tool in case of roughing. During the measurement, the light beam of a low-power He-Ne gas laser was reflected from the workpiece's surface. The scattered light was recorded with a digital camera and then analysed using appropriate image processing techniques. The average of the resulting pattern and its standard deviation for the intensity image were examined. This method can detect a roughness corresponding to 1/8 of the laser wavelength. Of course, to analyse the tool's wear, the quality of the surface, the optical parameters, and the tool degradation had to be matched. According to their experience, surface quality, tool wear and optical characteristics are not always consistent because they depend on many factors. The scattered laser pattern itself does not correlate with tool wear, but the intensity distribution of the pattern does – but only in a limited range of wear.

Self-excited vibrations were investigated by Prasad et al., but already during a series of experiments with LDV. In their study [38], they looked for the connection between the workpiece's vibration, the tool's wear, and the texture of the machined surface. During face turning, the vibration in the feed direction was measured with a laser. An FFT spectrum was formed from the received signal and then evaluated. By carrying out the measurements on different materials, with the sharp, the less worn, and finally, the blunt tool, they found that as the tool's wear progressed, the vibration amplitudes also increased in the frequency range - as expected. The further increase in vibration was attributed to the ever-increasing friction between the workpiece and the cutting tool, which is also a consequence of tool wear.

In another paper by Prasad, the cutting temperature and the dynamic characteristics of the vibration signals were analysed simultaneously [39]. LDV was used to extract the vibration data in the feed direction during orthogonal cutting, and the temperature was measured by infrared thermography. They aimed to create an experimental database to detect and monitor tool wear. Their experiments showed a relationship between vibrations, cutting temperature and tool wear, depending on the speed.

The article by Venkata Rao et al. [40] is related to turning but also touches on the next chapter, in which the authors analysed the effects of cutting speed, feed and tip radius of the cutting insert in hole turning. Vibrations in this process are especially problematic when the tool is still at the beginning of the hole machining and most of it is located outside the hole. The vibration of the workpiece was also monitored with the LDV. The roughness and wear parameters were compared with the vibration amplitudes by recording the FFT spectrum of the signal.

During hole turning, laser measurements were also performed in cases where the machining process is aided by externally generated vibrations [49]. Chern and Liang used a piezo crystal oscillator to vibrate the tool in the feed direction. They aimed to improve the crossing holes and reduce the surface roughness. At the intersection of the holes, even significant burrs can form, which, for example, cause problems with flow technology in the case of valves. In their tests, the laser played an additional role. The vibration amplitudes were analysed with a laser displacement meter. Its sampling frequency was 50kHz, while the frequency that excites the tool could be changed to 14kHz, so very high frequencies could also be tested.

3. LASER INSPECTION DURING DRILLING

Recently, several articles have been published about using LDV during drilling [36],[49–50], but it is by no means a commonly used method. Unlike previous material separation operations, drilling is even less common to use a laser as a sensor signal source. Nevertheless, this measurement method's advantages can be seen precisely during this cutting process.

Electronic non-contact measurement techniques, such as inductive and capacitive displacement sensors, offer limited possibilities for non-contact measurement. These are limited only to close measurements and are sensitive to thermal expansion. So, they must be arranged in two pairs for acceptable measurement [35]. With drilling, direct control of the cutting process is impossible – as it cannot be directly observed. Thus, only indirect measurement procedures help understand the process's phenomena during cutting, even when creating a TCM strategy. It is advisable to examine the tool's vibrations; for instance, individual chip removal steps can be better observed by measuring the tool itself [51].

Chern and Liang repeated the same vibration tests performed in hole turning for small diameter holes. The measuring range of the laser displacement meter (50kHz) made it possible to measure the excitation in the higher frequency range correctly.

During measurements during drilling, it was clearly observed that until (with fixed cutting parameters) the drill bit begins to cut with its total diameter, the individual temporal phases have a specific time and frequency range [50].

Balaji et al. deal with the effect of cutting speed, feed and groove angle on drilling tool life (wear) [52]. His study examined the tool's vibrations during drilling on a universal lathe with a Laser Doppler vibration meter. He determined the relationship between the vibration amplitudes and wear, groove angle, surface quality, and vibration parameters based on the measured data.

4. LASER MEASUREMENTS IN MILLING

Milling is the cutting operation that has been/is being researched the most due to its versatility. This is why we often come across laser devices during examinations. In their early work [53], Ryabov et al. used a laser to measure tool wear during the process and to detect medium and large tool defects. The measurement of noisy signals obtained under natural cutting conditions was based on laser displacement sensors, and two laser sensors were used simultaneously. The tool's cutting-edge shape was checked with the two lasers. In addition, the received signals were fed into the control system and used as a synchronisation signal for speed control. According to their experience, the reflection's characteristics depend on the light dispersion properties of the surface and the direction of the incident light beam. Based on the results obtained during practical measurements, average and worn surfaces can be clearly distinguished through the light intensity patterns resulting from the difference in the surface. However, they do not differ significantly in their dispersion properties.

The article by Tatar and Grin also analyses tool vibrations during high-speed milling [35]. Since, in the case of high-speed cutting when measuring spindle vibration, low-vibration signal transmission, disturbances in the bearings, and magnetic disturbances in the motor make classical measurements unreliable, a new sensor was chosen. The task was solved with a non-contact laser sensor placed near the tool. In experiments, LDV measured the speed of a given point of the tool and its displacement, thanks to the built-in system. This possibility is a real advantage in the lower frequency range. At the same time, due to the appearance of pseudo-vibrations and transverse vibrations from the shape of the tool shank, they had to perform additional measurements.

The topic of the work by Faassen et al. was self-excited vibrations occurring during high-speed milling [54]. While others use constant parameters for the entire spindle speed range to describe the machine dynamics and the behaviour of the cutting process, they proposed a model that also considers the spindle speed to construct the stability maps. In this model, the dynamics of the machine also play a role. To measure the dynamic behaviour of the main spindle-tool holder-tool system and determine the effect of the spindle speed on this behaviour, FRF (Frequency Response Function) tests were performed with an impulse hammer. Measurements were made with a stationary and rotating spindle, where the vibrations were recorded with a twin-sensor industrial laser (LTS – Laser Twin Sensor) surface inspection sensor. They could establish a frequency response characteristic in the range of 750–1750 Hz through laser measurement. The previous experiments were supplemented with microphone measurements to refine the stability limits.

Rantatalo's measurements were also made on a milling machine [55]. His method was primarily aimed at analysing the vibrations of the main spindle. In his complex work, he searched for an answer to the effect of the main spindle as a rotating element on the system's stability. Its solution is general, so it can also be used with other chucked devices.

The dynamic effect of the main spindle on cutting was also dealt with by Österlind and his research group [56], but unlike others, he used the method of in-process modal analysis (OMA – Operational Modal Analysis). For static measurements, the transfer functions were prepared with an impulse hammer, and then the parameters during the operation were recorded with an OMA. They also used several different sensors in their experiments. The vibrations of the workpiece, the tool holder and the table were measured with accelerometers. In contrast, the tool's response to vibrations was measured with a laser Doppler vibration meter. The measurement results were used to analyse the stability map of the system, examining the changes that occurred during cutting.

Self-excited vibrations have been a topic of interest to researchers for a long time. For example, in a previous article, Nakagawa et al. discuss the effects of vibrations generated during the milling of hardened steel materials on the surface quality [57]. Since the previously discussed eddy current sensor had both placement and dynamic disadvantages (detection threshold in the lower frequency range), the displacement of the milling tool tip was measured with an LDV. During measurement, two LDVs simultaneously monitored the operation and the mutually perpendicular displacements of the tooltip. They tried to correct the instrument's relative measurement error by placing it relatively far from the measurement point. During their experiments, with the help of high-resolution measurements, they identified two different types of self-excited vibrations. It was possible to observe the change in the unstable regions of the stability map.

The dynamic properties of the machine tool-tool-workpiece system were also investigated by Norman et al., during which LDV was used to predetermine the dynamic parameters of the system [58]. Since the stiffness of the machine tool itself changes due to the changing working conditions (e.g. due to the variable bearing stiffness depending on the speed), they prepared a test bench for their tests. The effects of various factors affecting the system's dynamics were checked. The response data measured with the LDV were monitored by examining different load cases. So, the system's transfer function was defined in such a way that the main spindle axis was in rotation all the time - i.e. during work. The results of their experiments confirmed the advantage of testing with non-contact methods that the disadvantages observed with traditional sensors, such as the mass load of the accelerometers or the error caused by the damping of the pulse hammerhead, do not occur during the measurement. The measurements can, therefore, be performed even while the tool is rotating so that the changes in the system's transfer functions determined at different rotation speeds can be monitored.

5. COMMON EXPERIENCES WITH LASER MEASUREMENTS

As with all sensor types, measurement errors with laser sensors are caused by the conditions of their installation since the measured speed signal is relative. During machining experiments for research purposes with the LDV measuring instrument, it is a problem that the device (due to its dimensions) can often only be used mounted on a stand [36], [59]. So, vibrations originating from the laser's "capture" conditions also appear at the output of the LDV [60–61]. However, isolation from the environment, which is an obvious solution, requires careful preparation. In addition, it is complicated to eliminate low frequencies, so this problem cannot be solved effectively. The author and several colleagues used an optical vibration-free table during his measurements in several different measuring setups. He experienced vibrations independent of the choice of stand and originating from the characteristics and design of the measuring device [62].

The idea of Halkon and Rothberg [63] offers a simple solution to the relativity of the speed signal as a source of error. It has been proven in practice that if an accelerometer is paired with a second one mounted anywhere on the instrument and aligned in the laser beam, it solves this problem well. In their experiments, the instrument was supplemented with two traditional acceleration sensors that measure the vibration in the laser's direction. If they measure in the same direction and are axisymmetric to the laser beam, the amplitude and phase spectra of the instrument's vibrations can be well corrected. However, in addition to favourable experiences, the correction may be impaired by the transverse sensitivity of the acceleration sensor. Regardless, it is not only the relativity of the measurement that causes problems but also the polarised coherence of the laser light. By itself, the interference pattern would be an applicable property, for example, if it were a matter of examining the quality of the surface. In the case of a light wave with this property, if the light illuminates an optically rough surface - and most surfaces are like this - then each small surface element will act as a point source of coherent light. Due to the uncorrelated light waves created in this way, a granular pattern of dark and light spots is formed on the detector due to the superposition. The sensor is several such, i.e. collects a spot pattern with one sampling shape, and the current output of the photodiode will be proportional to the sum of these instantaneous intensity distributions [64].

If the spot pattern changes space and time (for example, a rapid movement of the target perpendicular to the measurement direction or a sudden rotation), the Doppler signal - and thus the output of the detector – is modulated by the change in the pattern [65-66]. Therefore, the formation of pattern noise can be explained by the fact that the point illuminated by the laser during the vibration was not the same point during the entire movement period [67].

Nevertheless, in the case of vibration testing, it is a distinct disadvantage because the sample fluctuates almost randomly [35–36], [41]. The effect of the change in granularity on the measured signal can be reduced by averaging the measurements [68–69]. However, spurious vibrations arising from the "repetition" of the pattern due to rotation are still visible in the spectrum. Their name used in international literature is pseudo-oscillations [69–70]. Therefore, if the laser scans a workpiece or tool rotating at high speed, we will get disturbing peaks and higher-order harmonics in the frequency spectrum due to the effect [64–65], [69].

For the simplest solution to this problem, it seems that making an "optically smooth" surface for the measurements can be a good solution [35], [41], [58]. That is, on the one hand, a clean and, on the other hand, smooth polished surface must be created for good reflection. However, making such preparations or ensuring this condition permanently is not always possible. The question is similar to the speckle noise phenomenon occurring in remote sensing (or laser-based remote sensing – LIDAR – Light Detection and Ranging). Courville, although not working in the field of metal cutting, draws attention in their work to the fact that a single LDV with two properly positioned detectors in one line can simultaneously record two measurements, which will have independent speckle noise [71]. To reduce the noise of the spot, he recommends separating the signals in the frequency range and averaging the measurement series recorded with several sensors simultaneously. In this way, they can also record the orthogonal polarisation of light.

Vass and his fellow researchers developed an algorithm operating in a time domain to improve the reflected light's signal/noise ratio [72]. According to their experiments, if the spot pattern of the reflected light differs significantly from the majority of the samples in the signal (examined over time), i.e. the amplitude distribution of the sample does not follow the usual dispersion of the signal and shows an extreme deviation from the average. The peakedness (kurtosis) can be used to detect the disturbance. If outliers exceed a limit, they can be automatically removed. Hosek, who compared the effectiveness of this method with several techniques, also similarly limits the vibration amplitudes [66]. The disadvantage of the kurtosis method is that it is primarily suitable for detecting random and out-of-average scattering noise.

An additional, simple solution is to eliminate noise smearing errors caused by rotation is almost self-evident – if the cutting conditions permit – the measurement must be performed on the stationary tool [36], [40], [49], [51]. However, this limitation cannot be a condition for developing a condition-monitoring strategy.

6. SUMMARY

In summary, it can be said that laser measuring devices are used in different ways for different types of machining. Lasers came to the fore primarily for surface inspection and determining the dynamic behaviour of the machine system or process. The use of lasers in drilling among the machine manufacturing technological processes is still waiting to be discovered in contrast to milling or turning, which are well and effectively researched areas.

Interferometric measuring devices are more accurate than other laser measuring techniques, but their more complicated construction makes them more sensitive to the conditions. The triangular measuring technique, which is well-proven in practice, can also be used adequately for measurements during cutting. It is a method often used for research, but during production, it is currently used almost only in cases of positioning and coordinate measurement.

It is typical that the laser measuring technique is only one component of a more complex measuring system and takes on a complementary role alongside other types of measuring devices.

Indeed, the cutting or machining conditions are not always favourable for measuring methods where environmental effects can strongly influence the measurement results. However, with its advantages, laser technology can increasingly provide a suitable answer to the problems that arise during cutting.

ACKNOWLEDGEMENT

Project no. NKFI-125117 has been implemented with support from the National Research, Development and Innovation Fund of Hungary, financed under the K_17 funding scheme.

References: 1. The machine tool industry: three trends affecting it globally. [Online]. Available: https://www.etmm-online.com/the-machine-tool-industry-three-trends-affecting-it-globally-a-721307/. [Accessed: 03-Sep-2019]. **2.** *Ahmad, M. I., Yusof, Y., Daud, M. E., Latiff, K., Kadir, A. Z. A., Saif, Y.:* Machine monitoring system: a decade in review. International Journal of Advanced Manufacturing Technology, Vol 108, No 11–12., pp. 3645–3659, 2020. **3.** *Yi-Cheng, H., Chang-Chih, L., Po-Chou, C.:* Prognostic diagnosis of the health status of an air-turbine dental handpiece rotor by using sound and vibration signals. Journal of Vibroengineering, Vol 18, No 3, pp. 1514–1524, 2016. **4.** *Nath, C.:* Integrated Tool Condition Monitoring Systems and Their Applications: A Comprehensive Review. Procedia Manufacturing, Vol 48, pp. 852–863, 2020. **5.** *Kovač, P., Mankova, I.:* A review of machining monitoring systems. Journal of Production Engineering, Vol 14, No 1, pp. 8–13, 2011. **6.** *Zaghal, J.; Benke, M.*: Determination of Reliable Area Sizes for 3d Roughness Measurement, Cutting & Tools in Technological System, 98 pp. 3–12, 10 p., 2023. **7**. *Zhou, J., Han, X., Li, H., Liu, S., Shen, S., Zhou, X., Zhang, D.*: In-situ laser polishing additive manufactured AlSi10Mg: Effect of laser polishing strategy on surface morphology, roughness and microhardness, Materials 14, pp. 393, 2021. **8.** *Zhou, H., Zhou, H., Zhao, Z., Li, K., Yin, J.*: Numerical simulation and verification of laser-polishing free surface of S136D die steel, Metals 11, p. 400, 2021. **9.** *Lavrinenko, V., Fedorovich, V., Ostroverkh, Y., Solod, V.*: Modern Developments Related to the Directed Impact on the Cutting Surface of a Diamond Abrasive Tool and its Contact Zone in the Processes of Machining (review), Cutting & Tools in Technological System 98 pp. 13–28, 16 p.,2023. **10.** *Wei Zhou, Genyu Chen, Mengyang Gao, Mingquan Li*: Laser sharpening evaluation of diamond wheels based on 3Drecognition, Diamond and Related Materials, Vol 129, No 11, 109354, 2022. **11.** *Longzhou Dai, Genyu Chen, Mingquan Li, Shangyong Yuan*: Efficient and precision dressing of arc-shaped diamond grinding wheel by laser dressing and electrical discharge dressing, Diamond and Related Materials. Vol 125, No 5, 108978, 2022. **12.** *Molnar, V.*: Designation of Evaluation Area in Measuring 3D Surface Roughness, Cutting & Tools in Technological System 93, pp.56–64., 2020. doi:10.20998/2078-7405.2020.93.07 **13.** *Landers, R., Ulsoy, G., Furness, R.:* Process Monitoring and Control of Machining Operations. in Hurmuzlu, Y., Nwokah, O. D. I., The Mechanical Systems Design Handbook: Modeling, Measurement, and Control, (1st ed.), Ch 6, pp. 99–117, CRC Press, 2002. **14.** *Djurdjanovic, D., Mears, L., Niaki, F. A., Haq, A. U., Li, L.:* State of the Art Review on Process, System, and Operations Control in Modern Manufacturing. Journal of Manufacturing Science and Engineering, Transactions of the ASME, Vol 140, No 6, ASME, 2018. **15.** *Nishiguchi, T., Koizumi, Y., Maeda, Y., Masuda, M., Nagayama, K., Okamura, K.:* Improvement of Productivity in Aspherical Precision Machining with In-situ Metrology. CIRP Annals, Vol 40, No 1, pp. 367–370, 1991. **16.** *Zhou, Z., Yao, B., Xu, W., Wang, L.:* Condition monitoring towards energy-efficient manufacturing: a review. International Journal of Advanced Manufacturing Technology, Vol 91, No 9–12, pp. 3395–3415, 2017. **17.** *Goyal D.,* *Pabla, B. S.:* Condition based maintenance of machine tools - A review. CIRP Journal of Manufacturing Science and Technology, Vol 10, pp. 24–35, 2015. **18.** *Greenough, R. M., Grubic, T.:* Modelling condition-based maintenance to deliver a service to machine tool users. The International Journal of Advanced Manufacturing Technology, Vol52, pp. 1117–1132, 2011. **19.** *Chikuruwo, M. N. H., Maregedze, L., Garikayi, T.:* Design of an automated vibration monitoring system for condition-based maintenance of a lathe machine (Case study). in 2016 International Conference on System Reliability and Science, ICSRS 2016 - Proceedings, pp. 60–63, 2017. **20.** *Tandon, N., Parey, A.:* Condition Monitoring of Rotary Machines. in Wang, L., Gao, R. X., Condition Monitoring and Control for Intelligent Manufacturing, Springer Series in Adv. Man. (SSAM), pp. 109–136, 2006. **21.** *Elbestawi, Mo A., Dumitrescu, M., Ng, Eu-Gene:* Tool Condition Monitoring in Machining. in Wang, L., Gao, R. X., Condition Monitoring and Control for Intelligent Manufacturing, Springer Series in Adv. Man. (SSAM), pp. 55–82, 2006. **22.** *Ulsoy, A., G.:* Monitoring and Control of Machining. in Wang, L., Gao, R. X., Condition Monitoring and Control for Intelligent Manufacturing, Springer Series in Adv. Man. (SSAM), pp. 1–32, 2006. **23.** *Ghani, J. A., Rizal, M., Nuawi, M. Z., Ghazali, M. J., Haron, C. H. C.:* Monitoring online cutting tool wear using low-cost technique and user-friendly GUI. Wear, Vol 271, No 9–10, pp. 2619–2624, 2011. **24.** *Požar, T., Možina, J.:* Enhanced ellipse fitting in a two-detector homodyne quadrature laser interferometer. Measurement Science and Technology, Vol 22, No 8, 2011. **25.** *Cho, S., Binsaeid, S., Asfour, S.:* Design of multisensor fusion-based tool condition monitoring system in end milling. The International Journal of Advanced Manufacturing Technology, Vol 46, pp. 681–694, 2010. **26.** *Kuntoglu, M., Aslan, A., Saglam, H., Pimenov, D. Y.:* Optimization and Analysis of Surface Roughness Flank Wear and 5 Different Sensorial Data via Tool Condition Monitoring System in Turning of AISI 5140. Sensors, Vol 20, 2020. **27.** *Dimla, D. E. Snr.:* Sensor signals for tool-wear monitoring in metal cutting operations – a review of methods. International Journal of Machine Tools and Manufacture, Vol 40, No 8, pp.1073-1098, 2000. **28.** *Powell, R. L., Stetson, K. A.:* Interferometric Vibration Analysis by Wavefront Reconstruction. Journal of the Optical Society of America, Vol 55, No 12, pp. 1593-1598, 1965. **29.** *Sadílek, M., Kratochvíl, J., Petru, J., Čep, R., Zlamal, T., Stančeková, D.:* Cutting tool wear monitoring with the use of impedance layers. Tehnicki Vjesnik, Vol 21, No 3, pp. 639–644, 2014. **30.** *Donati, S., Norgia, M.:* Overview of self-mixing interferometer applications to mechanical engineering. Optical Engineering, Vol 57, No 5, pp 13, 2018. **31.** *Kurada, S., Bradley, C.:* A review of machine vision sensors for tool condition monitoring. Computers in Industry, Vol 34, No. 1. Elsevier, pp. 55–72, 1997. **32.** *Randall, R. B.:* Vibration based Condition Monitoring. John Wiley & Sons Ltd, Chichester, UK, 2011. **33.** *Downey, J., Bombiński, S., Nejman, M., Jemielniak, K.:* Automatic multiple sensor data acquisition system in a real-time production environment. Procedia CIRP, Vo. 33, pp. 215–220, 2015. **34.** *Li, Y., Zhu, J., Duperron, M., O'Brien, P., Schüler, R., Aasmul, S., de Melis, M., Kersemans, M., Baets, R.:* Six-beam homodyne laser Doppler vibrometry based on silicon photonics technology. Optics Express, Vol 26, No 3, pp. 3638-3645, 2018. **35.** *Tatar, K., Gren, P.:* Measurement of milling tool vibrations during cutting using laser vibrometry. International Journal of Machine Tools and Manufacture, Vol 48, No 3–4, pp. 380–387, 2008. **36.** *Béres, M., Paripás, B.:* Measuring of drill bit vibration by laser Doppler methods. IOP Conference Series: Materials Science and Engineering, Vol 448, No 1, 2018. **37.** *Rizal, M., Ghani, J. A., Nuawi, M. Z., Haron, C. H. C.:* An embedded multi-sensor system on the rotating dynamometer for real-time condition monitoring in milling. The International Journal of Advanced Manufacturing Technology, Vol 95, pp. 811–823, 2018. **38.** *Prasad, B. S., Sarcar, M., Ben, S.:* Development of a system for monitoring tool condition using acousto-optic emission signal in face turning-an experimental approach. The International Journal of Advanced Manufacturing Technology, Vol 51, No 1, pp. 57–67, 2010. **39.** *Prasad, B. S., Prabha, K. A., Kumar, P. V. S. G.:* Condition monitoring of turning process using infrared thermography technique – An experimental approach. Infrared Physics & Technology, Vol 81, pp. 137–147, 2017. **40.** *Rao, K.V., Murthy, B., Rao, N. M.:* Experimental study on tool condition monitoring in boring of AISI 316 stainless steel. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol 230, No 6, pp.1144–1155, 2016. **41.** *Tatar, K., Rantatalo, M., Gren, P.:* Laser vibrometry measurements of an optically smooth rotating spindle. Mechanical Systems and Signal Processing, Vol 21, No 4, pp. 1739–1745, 2007. **42.** *Lee, Y.,* *Dornfeld, D. A.:* Application of Open Architecture Control System in Precision Machining. 31st CIRP International Seminar on Manufacturing Systems, Berkeley, CA, May 1998. **43.** *Bhuiyan, M. S. H., Choudhury, I. A.:* Review of Sensor Applications in Tool Condition Monitoring in Machining. Comprehensive Materials Processing, Vol. 13, pp. 539–569, 2014. **44.** Urbikain, G., Olvera, D., de Lacalle, L. N. L., Elías-Zúñiga, A.: Spindle speed variation technique in turning operations: Modeling and real implementation. Journal of Sound and Vibration, Vol 383, pp. 384–396, 2016. **45.** *Kiss, A. K., Bachrathy, D., Stepan, G.:* Laser scanned patterns of machined surfaces. Procedia CIRP, Vo. 77, pp. 355–358, 2018. **46.** *Sun, H.:* Modeling the near-field and far-field modes of single spatial mode laser diodes. Optical Engineering, Vol 51, No 4, 2012. **47.** *Naqwi, A., Durst, F.:* Focusing of diode laser beams: a simple mathematical model. Applied Optics, Vol 29, pp. 1780–1785, 1990. **48.** *Wong, Y. S., Nee, A. Y. C., Li, X. Q., Reisdorf, C.:* Tool condition monitoring using laser scatter pattern. Journal of Materials Processing Technology, Vol 63, No 1–3, pp. 205–210, 1997. **49.** *Chern, G. L., Liang, J. M.:* Study on boring and drilling with vibration cutting. International Journal of Machine Tools & Manufacture, Vol 47, No 1, pp. 133–140, 2007. **50.** *Béres, M., Paripás, B.:* Fúrószár rezgéseinek mérése lézer Doppler módszerrel. Proc. XXXI. MicroCAD International Multidisciplinary Scientific Conference, University of Miskolc, Hungary, 20–21 April 2017. **51.** *Béres, M., Paripás, B.:* Measurements of vibration by laser Doppler method in the course of drilling. Lecture Notes in Mechanical Engineering, Vol 0, No. 1, pp. 199–208, 2018. **52.** *Balaji, M., Murthy, B. S. N., Rao, N. M.:* Optimization of Cutting Parameters in Drilling of AISI 304 Stainless Steel Using Taguchi and ANOVA. Procedia Technology, Vol 25, pp. 1106–1113, 2016. **53.** *Ryabov, O., Mori, K., Kasashima, N., Uehara, K.:* An In-Process Direct Monitoring Method for Milling Tool Failures Using a Laser Sensor. CIRP Annals. – Manufacturing Technology, Vol 45, No 1, pp. 97–100, 1996. **54.** *Faassen, R. P. H., Van de Wouw, N., Oosterling, J. A. J., Nijmeijer, H.:* Prediction of regenerative chatter by modelling and analysis of high-speed milling. International Journal of Machine Tools and Manufacture, Vol 43, No. 14, pp. 1437–1446, 2003. **55.** *Rantatalo, M.:* Non-contact measurements and modelling of milling machine tool vibrations. Ph.D. thesis/ LuleÂ University Technol., ISSN: 1402–1757, 2006. **56.** *Österlind, T., Frangoudis, C., Archenti, A*.: Operational modal analysis during milling of workpiece, fixed on a stiffness controllable joint. Journal of Machine Engineering, Vol 13, 2013. **57.** *Nakagawa, H., Kurita, Y., Ogawa, K., Sugiyama, Y., Hasegawa, H.:* Experimental analysis of chatter vibration in end-milling using laser Doppler vibrometers. International Journal of Automation Technology, Vol 2, No 6, pp. 431-438, 2008. **58.** *Norman, P., Bäckström, M., Rantatalo, M., Svoboda, A., Kaplan, A.:* A sophisticated platform for characterization, monitoring and control of machining. Measurement science and technology, Vol 17, No 4, pp. 847, 2006. **59.** *Béres, M., Paripás, B.:* Comparison of two laser interferometric methods for the study of vibrations, in Vehicle and Automotive Engineering, Part of the Lecture Notes in Mechanical Engineering book series (LNME), pp. 205–216. Springer, 2017. **60.** *Majár, J., Béres, M., Kovács, E.:* Effect of Different Supports on the Systematic Errors in Laser Doppler Measurements. Proc. MultiScience – XXXIII. microCAD, International Multidisciplinary Scientific ConferenceUniversityofMiskolc, 23–24. May 2019. **61.** *Munoa, J., Beudaert, X., Dombovari, Z., Altintas, Y., Budak, E., Brecher, C., Stepan, G.:* Chatter suppression techniques in metal cutting. CIRP annals, Vol 65, No 2, pp. 785–808, 2016. **62.** *Norgia, M., Melchionni, D., Pesatori, A.:* Self-mixing instrument for simultaneous distance and speed measurement. Optics and Lasers in Engineering, Vol 99, pp. 31–38, 2017. **63.** *Halkon, B. J., Rothberg, S. J.:* Taking laser Doppler vibrometry off the tripod: correction of measurements affected by instrument vibration. Optics and Lasers in Engineering, Vol 91, pp. 16–23, 2017. **64.** *Halliwell, N. A.:* The laser torsional vibrometer: a step forward in rotating machinery diagnostics. Journal of sound and vibration, Vol 190, No 3, pp. 399–418, 1996. **65.** *Rothberg, S. J., Allen, M. S., Castellini, P., Di Maio, D., Dirckx, J. J. J., Ewins, D. J., … , Vignola, J. F.:* An international review of laser Doppler vibrometry: Making light work of vibration measurement. Optics and Lasers in Engineering, Vol 99, pp. 11–22, 2017. **66.** *Hosek, P.:* Algorithm for signal drop-out recognition in IC engine valve kinematics signal measured by laser Doppler vibrometer. Optics & Laser Technology, Vol 44, No 4, pp. 1101–1112, 2012. **67.** *Drain, L. E.:* The laser Doppler techniques. Chichester, 1980. **68.** *Bell, J. R., & Rothberg, S. J.:* Laser vibrometers and contacting transducers, target rotation and six degree-of-freedom vibration: what do we really measure? Journal of Sound and Vibration, Vol 237, No 2, pp. 245–261, 2000. **69.** *Rothberg, S. J., Baker, J. R., Halliwell, N. A.:* On Laser Vibrometry of Rotating Targets: Effects of Torsional and In-Plane Vibration. Journal of Laser Applications, Vol 2, No 1, pp. 29–36, 1990. **70.** *Martin, P., Rothberg, S.:* Introducing speckle noise maps for laser vibrometry. Optics and Lasers in Engineering, Vol 47, No 3–4, pp. 431–442, 2009. **71.** *Courville, S. W.:* Toward orbital seismology: theory for speckle noise reduction in laser Doppler vibrometer measurements on distant rough surfaces. Colorado School of Mines ProQuest Dissertations Publishing, No 27662723, 2019. **72.** *Vass, J., Šmíd, R., Randall, R. B., Sovka, P., Cristalli, C., Torcianti, B.:* Avoidance of speckle noise in laser vibrometry by the use of kurtosis ratio: Application to mechanical fault diagnostics. Mechanical Systems and Signal Processing, Vol 22, No 3, pp. 647–671, 2008.

Міклош Береш**,** Дьюла Варга, Мішкольц, Угорщина

ЛАЗЕРНІ ВИМІРЮВАННЯ В ПРОЦЕСАХ РІЗАННЯ

Анотація. *Метрологія на місці у виробничих системах підвищує точність і скорочує час обробки за рахунок виключення операцій перепозиціонування і установки. Досягти цих цілей допомагають різні методи і прийоми моніторингу. Ці процедури набувають все більшого значення в окремих технологічних операціях виробництва. Деякі процедури моніторингу стану контролюють верстат, тоді як інші зосереджуються безпосередньо на інструменті. Перший в основному зосереджений на технічному обслуговуванні на основі стану, надаючи дані, які можуть доповнити стратегію технічного обслуговування на основі оцінки ризику (пропонуючи серйозну економічну перевагу для користувачів). Інші методи моніторингу максимізують дорогоцінний робочий час, витрачений на якісне виробництво, досліджуючи стан інструменту. Сьогодні в нашому розпорядженні є безліч різних датчиків і методів вимірювання. Однак кожен з них має обмеження, тому вимірювання все одно обтяжене похибками. Чим чутливіший метод вимірювання (наприклад, лазерний) до фізичного сигналу, тим точніше він може відтворити досліджуване явище. З цієї точки зору вони, таким чином, мають певну перевагу. Нові сфери застосування виходять на перший план завдяки мініатюризації та вбудовуванню вимірювальних приладів. Прикладом такого пристрою є багатопроменевий, інтегрований напівпровідниковий лазер. У порівнянні з попередніми пристроями, цей новий шестипроменевий лазерний чіп зменшує втрати, спричинені часом виявлення, і підвищує стабільність сигналу. Розробка дуже вигідна для вимірювання вібрацій в низькочастотному діапазоні, з амплітудою до 100 мкм/с, роздільною здатністю і якістю, подібними до комерційно доступних LDV. Лазери вийшли на перший план насамперед для поверхневого контролю та визначення динамічної поведінки машинної системи або процесу. Використання лазерів у свердлінні серед технологічних процесів машинобудування все ще чекає свого відкриття, на відміну від фрезерування або токарної обробки, які є добре та ефективно дослідженими галузями. Інтерферометричні вимірювальні прилади більш точні, ніж інші лазерні вимірювальні методи, але їх більш складна конструкція робить їх більш чутливими до умов. Трикутна методика вимірювання, яка добре зарекомендувала себе на практиці, також може бути адекватно використана для вимірювань під час різання. Це метод, який часто використовується для досліджень, але під час виробництва в даний час він використовується майже тільки у випадках позиціонування та вимірювання координат.*

Ключові слова: *різання металу; лазерне вимірювання; технологічний моніторинг; LDV; оптичні датчики.*