Method of measuring the abrasive-water jet diameter, for the cutting process control

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1. Introduction

Abrasive water jet cutting is a new and very efficient industrial technology that has plenty of applications for all kinds of materials, whatever their nature, as well as thickness up to 200 mm. This technology process is the object of many research papers [1-6], which aim to increase the quality level of the cutting operations for various materials, shapes and requirements. The technical level of the machines for this process has also grown steadily [7-10].

This paper presents a system and a method for measuring the diameter of the water jet, by the process of cutting by water jet with abrasive. The goal of the method is the real time adjusting of the diameter of the abrasive-containing water jet, as well as adjusting the other parameters of this process, to raise the quality level of cuts, depending on the material to be processed. Measuring the diameter of the abrasive water jet nozzle at the outlet of the cutting head should be carried out indirectly, as direct measurement is not possible or is difficult in view of the impact force of the jet. For measuring the diameter of the abrasive water jet a method should be applied which uses an intermediate model that allows a high degree of proportionality to the original that is the abrasive water jet, as a physical entity.

The method of measuring the diameter of the abrasive water jet is one of the methods for checking the operating parameters of equipment, plants and industrial machinery, namely real time monitoring the operating parameters, but it is also part of the active intervention on these parameters, by corrections imposed on them, in order to improve the results of the operations performed. Archiving the operating parameters according to the requirements of the quality management system is another objective of the method.

In particular, the method is applicable to systems for positioning and actuating, which are based on the measurement of dimensions, by the recognition of certain images and comparison thereof to specific patterns, with or without computer-based control.

2. Operating characteristics

In the present situation, the operating characteristics of the jet of water and abrasive by the cutting operations of this process are determined by the manufactured shape of the cutting head and the parameters of the cutting process with an abrasive-containing water jet: pressure of 3000...4000 bar brought out by a high pressure pump; water flow rate; abrasive flow rate; diameter of 0.5...0.7 mm of the cutting-head outlet nozzle, made of a material of high hardness and abrasive wear withstand (sapphire, diamond, etc.); the gap from the nozzle outlet end to the surface of the material to be cut; thickness of the material to be cut; technological cutting speed, respectively the speed components v_x, v_y and v_z related to the axes O_x, O_y and O_z of the displacement coordinate system; variations of the speed components, respectively acceleration components by the three-axis, since they cause inertia forces acting on the abrasive water jet column, instantly changing its shape and direction.

In the Figure 1, a type of equipment for abrasive water jet cutting is presented.

Figure 1. Equipment for abrasive waterjet cutting.

The content of abrasive material (crystallized hard rocks, with polyhedral crystalline form, grain size of 0.3...0.7 mm) of the water jet has the effect of amplifying the inertial forces due to the 2.0...2.5 times higher density of the abrasive, compared to water. There are also other factors that influence the size and shape of the abrasive water jet, mainly the jet diameter. In particular the nature of the material to be cut has an important role by the impact withstand exerted to the fluid column of the abrasive water jet, dynamically modified by the impact withstand during the cutting process, depending on the instantaneous evolution thereof, which depends, in turn, on the microscopic processes that take place at the collision impact of the abrasive particles with the material to be cut, while the latter may have a crystalline structure with large or small size grains, respectively an amorphous structure.

In the Figure 2, the abrasive water-jet cutting process on a 10 mm steel plate is illustrated.

Figure 2. Abrasive water-jet cutting process on a 10 mm steel plate.

The main role on the shape and dimensions of the abrasive water jet, in particular on the jet diameter, has the diameter of the calibrated orifice (0.5...0.7 mm) of the outlet nozzle of the cutting head. In the initial stage, this hole is set at a certain diameter value, but the hole gets worn during time under the influence of abrasive particles impact, even if the nozzle is made of a material with high withstand to wear. This has the effect of increasing the hole diameter, respectively the diameter of the abrasive water jet passing through the calibrated nozzle diameter. Measuring the diameter of the abrasive water jet has also the role to determine the wear degree of the calibrated nozzle diameter, in order to replace it. Measuring the diameter of the abrasive water jet is not only limited to this operation itself. The main goal is to manipulate the individual process parameters for obtaining certain real-time corrections of the shape, sizes, appearance, properties and characteristics of the cut, respectively the quality level of the cut and pieces obtained by cutting.

3. Present measuring methods

In the state of the art, measuring the diameter of the abrasive water jet during the cutting process is not performed, under the industrial application conditions of this process. There are no such known methods of measuring the diameter of the abrasive water jet in the research stage of the abrasive water jet cutting process.

By calibrating the inner diameter of the outlet nozzle of the cutting head, an empirical correlation is established between the diameter of the calibrated nozzle and the quality of the workpieces obtained by cutting, but without any direct or real time intervention on the cutting process, to correct its running mode. Correction of the results may be done only for the following cutting operations, by replacing the worn nozzle with a nozzle having a different diameter. The obtained results will be compared and a selection will be made.

This is an indirect method of evaluating the effect of the diameter of the abrasive water jet on the quality level of parts resulting from the cut. Specifically, the outlet nozzle diameter is measured and the diameter of the abrasive water jet is actually estimated. But the diameter of the water jet is influenced by other factors, too, apart from the calibrated nozzle diameter at the outlet of the cutting head, given that the nozzle calibration is off after some time of use, but time-based variation of the diameter offset compared to the initial value is unknown.

Current methods for estimating the diameter of the abrasive water jet are indirect methods based on mechanical principles, and they have the following disadvantages: results of the assessments can have relatively large errors, in the range 2...15%, because no direct measurements are carried out, but only estimates; neglecting the effect of other parameters and factors on the jet diameter; estimating the jet diameter does not introduce any correction of the process parameters effectively during the cutting process, but only after the cutting process, for other cutting operations, which result in other parts. Instead, the workpiece that has already been executed by abrasive water jet cutting, using an improper nozzle diameter, cannot be real-time corrected, related to the quality of the cut.

4. Proposed measuring method

The proposed solution solves the problem of the lack of a method for measuring the diameter of the abrasive water jet for industrial applications of cutting, as well as difficulties of current methods of indirect diameter estimation. This method is based on a new principle, namely using an intermediate model of the water jet. For the application of this method, the following conditions must be met:

1. The intermediate model must be accessible by the present technology of information and data processing;
2. The intermediate model must be proportionate with the original object, which is the abrasive water jet;
3. The entire system for indirect measurement must be properly calibrated, related to a standard model. In this situation, the hypothesis can be stated that it is possible to apply a method using as intermediate model the image of the original physical object. The method proposes to process the image of the abrasive water jet, for the purpose of indirect measurement of the jet diameter. By this method, other dimensions can also be measured. Thus, the shape of the water jet or other object can be compared with a standard form.

The proposed method for measuring the diameter of the abrasive water jet is described below. The water jet is transformed from a physical object into an equivalent image, on an electronical base, which is a signal of another physical nature. Measuring the diameter takes place on this image. Although changes of a physical quantity to another one and change of physical nature of the signals used requires some simplifying assumptions, and they can attract to themselves errors of lack of proportionality, it is considered and it can be shown that errors in this case are under a certain accepted limit and the measuring principle is correct and accurate.

The method is based on the use of the abrasive water jet image and measuring the diameter on this image, performed by a high definition video camera which provides a high resolution of the picture, at the state of the art in the field of imaging. This removes the difficulty of measuring directly, since it is not possible or is difficult, given the destructive force of impact of the jet. For measuring the diameter of the abrasive water jet on its image, software dedicated to the pattern recognition and interpretation is applied, elaborated for this aim.

5. Advantages of the new method

The method of measuring the diameter of the abrasive jet of water, as shown, has the following advantages:

1) It proposes an intermediate model of the abrasive water jet for indirectly measuring the jet diameter, as direct measurement is difficult or impossible, because of the destructive effect of the jet on measuring devices or instruments. The intermediate model is proportional to the original and the degree of proportionality is high. The intermediate model is accessible by technology of state of the art. An intermediate model is necessary, having linear dependence function of size and size variation speed, in order to perform measurements with an index of high fidelity, on this model.

2) It is possible to use certain devices of the imaging technique and informatics technology, having a class of high precision, specific to the digital devices for receiving and processing images on electronic pattern and comparing them with certain reference standard models, in order to determine deviations from the standards considered.

3) It allows comparison with a standard model or a size caliber, to determine the exact diameter and other sizes that play a role in regulating the process parameters for abrasive water jet cutting. Abrasive water jet image is influenced by many factors. In terms of size, the diameter of the jet image is depending on the distance from the target area of the water jet to the video camera that takes the jet image. Other dimensions of other elements of interest for the process control depend on the tilt angles of viewing, related to the axes of a coordinate system corresponding to the target element. Certain mathematical relationships can be established, for the calculation of the actual size compared to the target image size. Necessary calculations can be performed by the specialized software for image recognition and interpretation. But it is more efficient to compare the abrasive-water jet image or other object images, to the image of a standard model placed very close to the jet, respectively other objects. Thus, the image of the targeted object is affected by geometrical relations or other factors, in the same way as the standard model, which has as a consequence that the offsets of the diameter or other sizes of the water jet can be related to the diameter or other dimensions of the standard model. All these items are solved by the specialized software of the measurement system.

4) It provides acquisition of the measurement results unto the computer of the system for measuring the diameter of the abrasive water jet, as well as the use of measurement results for certain settings and control of the cutting process. The acquisition of results is carried out with a sampling frequency of at least 1... 10 kHz, so that the measurements are processed in real time by the digital controllers equipped with specific software for each parameter of the cutting process, in the frame of the centralized multifunction management system of the cutting process.

5) The system has a cost comparable to other digital systems for computer-based measurement and management of industrial processes. The cost of the computer-based measurement system should be related to the production amount of the cutting machine, to determine the duration of investment payback. If the recovery time is too long, some other applications must be found for the computer-based control system, with the same software or other software categories, which is sometimes possible, due to the multifunctional and flexible character of computerized systems.

6) The value of the ratio price / performance is very advantageous for the case of intensive use of the abrasive-water jet cutting machine. The performances of the measurement and control system will have a high level, as it is considered a computer system equipped with high level software developed for image recognition, real-time control and management processes. The expenditure for the computer-based system and peripheral interconnected devices, especially for the dedicated software that is developed are at the cost level of other automation and control systems of similar industrial processes. Comparison with classical measurement methods based on instruments, devices or transducers for measuring dimensions, is not justified, because many of the gauges mentioned in this class are based on analogue principles and cannot be used or do not have a sufficient level of precision. Mechanical instruments or mechanical parts of the sensors, for example, cannot be used because of the destructive effect of the abrasive water jet upon them.

6. Measuring system

The Figure 3 shows the system for measuring the diameter of the abrasive water jet, for driving the cutting process, which applies the proposed method.

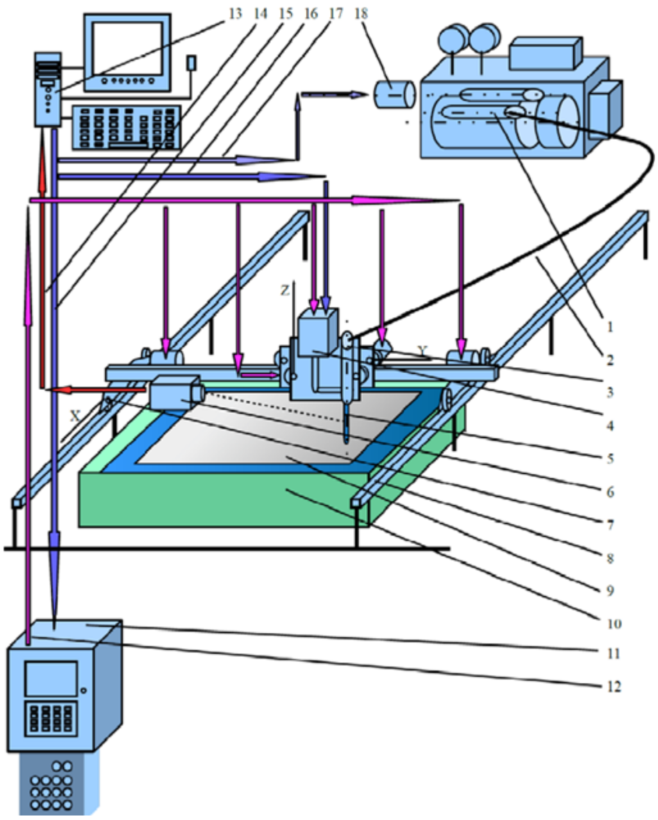

Figure 3. System for measuring the diameter of the abrasive water jet on a cutting machine.

The system for measuring the diameter of the abrasive water jet for the control of the cutting process consists of the following units: a high-pressure pump (1), which sends the water at a pressure of 3000...4000 bar, through the flexible high-pressure pipe (2), to the cutting head (3), where the high-speed water flow receives abrasive particulate from the abrasive dispencer (4) by means of a circuit which uses compressed air as a carrier, to form an abrasive water jet (5), having high speed and high kinetic energy. The video camera (6) takes the picture of the abrasive water jet.

The camera is displaced on the X-Y-Z coordinates travel system of an abrasive water jet-based cutting machine (7), moving on a runway (8). The abrasive water jet (5) carries out the cutting of a material piece (9), having the thickness in the range 0.5... 250 mm, depending on the nature of the material, for which there are no restraints. The material is placed in a tub (10) filled with metal balls or river stones, which take the impact of the abrasive water jet after the jet gets out of the cut material. In this tub, the jet of water is collected. The whole machine is driven by the command and numerical control unit CNC (11), linked with all components of the cutting machine by the bus (12) for data and supply voltages of the drives.

The computer (13) receives by the data bus (14) the video signal from the video camera (6). The computer is equipped with specific software for image recognition, image processing and decisions on adjusting certain parameters of the cutting process, in order to conduct the cutting process. For this aim, the computer transmits real-time correction signals via the data bus (15) to the CNC control unit (11) of the machine, respectively by the bus (16) to the dispenser of abrasive powder (4), as well as by the data bus (17) to the actuator (18) that performs corrections of the pre-set pressure at the high-pressure pump (1).

The assembly of the components described, having the characteristics and functions as determined depending on the technology and defined by the technique, represents the measuring system of the abrasive water jet diameter for the cutting process control, as an object of an original principle. This system implements the method of measuring the abrasive water jet diameter for the cutting process control, as an original concept.

7. Applications

The proposed method of measuring the diameter of the abrasive-water jet for controlling the cutting process, as above described, uses the image of the abrasive water jet (5), as an intermediate model for measuring, in such a way that the image is taken by a video camera (6) and it is processed by a computer (13), equipped with specialized software for image recognition and processing, as well as decision on necessary parameter adjustments and control of the cutting process. The computer transmits real-time correction signals via the data bus (15) to the CNC unit (11) that controls the machine, respectively by the bus (16) to the abrasive powder dispenser (4), as well as by the data bus (17) to the actuator (18) that performs correction of the pre-set pressure at the high-pressure pump (1). All corrections applied have the role to adapt the running of the cutting process, to increase the quality level of the cut, respectively of parts obtained by cutting, so that the sequence of operating steps described defines the method for measuring the diameter of the abrasive water jet, for controlling the cutting process.

The method can be applied in the industry, by adapting to abrasive water-jet cutting machinery, especially to such machinery that performs cutting operations on various material kinds, related to material nature and thickness, providing a way to real-time monitoring the shape and diameter of the abrasive water jet, as an item on which the shape, appearance and cut quality depends, as well as the part quality itself. Monitoring has also an active effect, as size deviations of the abrasive water jet are used by a computer-based system for corrections of the operating parameters of the machine, in order to adjust the values of process parameters and optimize the cutting process, depending on the actual operation way. The process of abrasive water jet cutting is a relatively new process. Such machines are already in the industrial exploitation. Thus, the method can contribute to increasing the technical level of these machines.

This method is also applicable to other types of equipment, where there is a jet of water or other fluid, as a functional element. A possible example is the use in research, of the image of the water jet or flow, to improve the turbulent flow regime in hydraulic turbines, in order to reduce the destructive effects of cavitation and increase efficiency. Another possible example refers to various hydraulic equipment, where similar technical problems can be solved, like the oil flow shape, in research aimed to improve these facilities.

8. Conclusions

The method of measuring the diameter of the abrasive water jet is one of the methods for checking and real-time monitoring the operating parameters of equipment, plants and industrial machinery. The method also performs the active intervention by corrections on these parameters, in order to improve the operation.

The operating characteristics of the jet of water and abrasive are determined by the manufactured shape of the cutting head and the parameters of the cutting process with an abrasive-containing water jet: pressure of 3000...4000 bar; water flow rate; abrasive flow rate; diameter of 0.5...0.7 mm of the cutting-head outlet nozzle; the gap from the nozzle outlet end to the surface of the material to be cut; thickness of the material to be cut; technological cutting speed, respectively the speed components v_x, v_y and v_z; acceleration components; inertia forces acting on the jet.

The content of abrasive material (crystallized hard rocks, grain size of 0.3... 0.7 mm) of the jet has the effect of amplifying the inertial forces due to the 2.0...2.5 times higher density of the abrasive, compared to water. Nature of the material to be cut has an important role by the impact withstand exerted.

The main role on the shape and dimensions of the abrasive water jet, in particular on the jet diameter, has the diameter of the calibrated orifice (0.5...0.7 mm) of the outlet nozzle of the cutting head.

In the state of the art, measuring the diameter of the abrasive water jet during the cutting process is not performed.

Current methods only estimate the diameter of the abrasive water jet. They are indirect methods based on mechanical principles. The results can have errors in the range 2...15%.

The proposed method is based on a new principle, namely using an intermediate model of the water jet, under the following conditions: the intermediate model must be accessible, apply the proportionality principle, respectively the entire measuring system must be properly calibrated.

The method of measuring the diameter of the abrasive jet of water, as shown, has the following advantages:

1) It allows an intermediate model of the abrasive water jet to be used for indirectly measuring, as direct measurement is difficult or impossible, because of the destructive effect of the jet.

2) It is possible to use certain devices of the digital imaging technique, having a class of high precision.

3) It allows comparison with a standard model or a size calibre.

4) It provides acquisition of the measurement results unto a computer.

5) The system has a cost comparable to other digital systems for computer-based measurement and control of industrial processes.

6) The value of the ratio performance / cost is very advantageous in the case of intensive use of the abrasive-water jet cutting machine.

The system for measuring the diameter of the abrasive water jet for the control of the cutting process consists of the following components: high-pressure pump (1), flexible high-pressure pipe (2), cutting head (3), abrasive dispencer (4), abrasive water jet (5), video camera (6), X-Y-Z coordinates travel system of a cutting machine (7), runway (8), material piece (9) to be cut, tub (10), numerical command and control unit CNC (11), bus (12) for data and supply, computer (13), data bus (14) for video signal, corrections bus (15), bus (16) for the dispenser, commands bus (17) and actuator (18).

The proposed method of measuring the diameter of the abrasive-water jet for controlling the cutting process uses the image of the abrasive water jet, as an intermediate model for measuring, in such a way that the image is taken by a video camera and it is processed by a computer, that transmits correction signals to the cutting machinery, to improve the process.

The method can be applied in the industry for abrasive water-jet cutting machinery. Monitoring has also an active effect, by corrections to adjust the process parameters. Thus, the method can contribute to increasing the technical level of these machines.

This method is also applicable to improve the turbulent flow regime in hydraulic turbines, in order to reduce the destructive effects of cavitation, as well as to various hydraulic equipment items, to correct the oil flow shape.

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References

[1]. Momber A. W., Kovacevic R.: ”Principles of abrasive water jet machining”. Springer, ISBN 3-540-76239-6, Berlin 1998.

[2]. Boud F., Loo L.F., Kinnell P.K.: ”The Impact of Plain Waterjet Machining on the Surface Integrity of Aluminium 7475”. Procedia CIRP, Volume 13, 2014, Pages 382-386. 2nd CIRP Conference on Surface Integrity. www.sciencedirect.com/science/article

[3]. Krajcarz D.: ”Comparison Metal Water Jet Cutting with Laser and Plasma Cutting”. Procedia Engineering, Volume 69, 2014, Pages 838-843. 24th DAAAM International Symposium on Intelligent Manufacturing and Automation, 2013. www.sciencedirect.com/science/article

[4]. A. Alberdi; A. Suárez; T. Artaza; G.A. Escobar-Palafox; K. Ridgway: ”Composite Cutting with Abrasive Water”. Procedia Engineering, Volume 63, 2013, pp. 421-429. The Manufacturing Engineering Society International Conference, MESIC 2013.

[5]. www.sciencedirect.com/science/article

[6]. Birtu C., Avramescu V.: ”Abrasive water jet cutting - technique, equipment, performances”, Non-conventional Technologies Review, Vol. 16(1), March 2012, pp. 40-46.

[7]. Miranda R.M., Quintino L.: ”Microstructural study of material removal mechanisms observed in abrasive waterjet cutting of calcareous stones”, Materials Characterization, Vol.54(4), 2005, pp.370-377.

[8]. International Waterjet Machines: ”IWM Waterjet/plasma cutting machines and services”. www.iwmwaterjet.com

[9]. Flow International Corporation: “The World’s Most Popular Waterjet”. www.flowwaterjet.com

[10]. Uhde High Pressure Technologies: “Engineered Solutions in High Pressure”. www.uhde-hpt.com

[11]. Waterjets.org: “How do waterjets work?”. www.waterjets.org.