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Uvod v diagnostiko postopka razslojevanja kompozitnih materialov pri rezanju z visokotlačnim abrazivnim vodnim curkom

An Introduction to the Diagnosis of the Delamination Process for Glass/Epoxy Composites During High-Pressure Abrasive Water-Jet Cutting

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Razslojevanje je glavna težava pri rezanju z vlakni ojačanih kompozitnih materialov z abrazivnim vodnim curkom. Je specifični pojav pri obdelavi kompozitnih materialov in je neodvisna od metode obdelave. V prispevku je predstavljen zamisel diagnostičnega sistema, ki temelji na digitalni časovni in frekvenčni analizi zajetih signalov za sprotno spremljanje razslojevanja kompozitnih materialov, ojačanih s steklenimi vlakni. Opisana je uporabljena merilna oprema ter prikazani so rezultati raziskave.

(Ključne besede: diagnostični sistemi, materiali kompozitni, rezanje s curkom, curek vodni, curek abrazivni)

The main problem during the abrasive water-jet cutting of fibre-reinforced composites is delamination. This delamination is a phenomenon specific to composite materials, which is independent of the machining method used. In this paper the concept of a diagnostic system is presented, based on a digital time and frequency signal analysis, for the online detection of the delamination in glass-fibre-reinforced composites. The applied measurement equipment is described and the research results are presented.

(Keywords: diagnostic systems, composites materials, abrasive water jet cutting)

0 INTRODUCTION

The advanced development of the electrical and machine-building industries as well as other branches of technology have created the rapid growth of the applications of new generations of construction materials, including composites fulfilling the requirements for high mechanical strength, the exploitation of which may replace commonly used traditional materials. One of the obstacles to the application of composite materials based on glass and carbon fibre is their mechanical workability, limiting the desired parameters of the technological quality, efficiency and purity of the end-product. The classical methods of cutting and machining that are used have many disadvantages, such as fast glazing of the cutting edge ([1] to [5]) overheating of both the material and of the tool ([3] and [6]), dusting of the reinforcing fibres ([2], [3] and [5]), and limitations on the shapes of the forms produced. These problems stimulated a search for new methods to work the material. Among them, the technology of high-pressure abrasive water-jets is of the highest importance. Recent developments in this technology make it possible to form composite elements with highly complex shapes in 2D and 3D [7].

1 DELAMINATION PHENOMENON OF THE COMPOSITE MATERIAL

The delamination of the material is a new and not completely understood phenomenon accompanying the cutting of composite materials with an abrasive water-jet under high pressure. The material damage is caused by the loss of coherence of the individual adjoining layers of the composite [8]. When cutting with an abrasive water-jet, delamination occurs in the external layers at the water outlet alongside the cutting edge (see Figure 1).

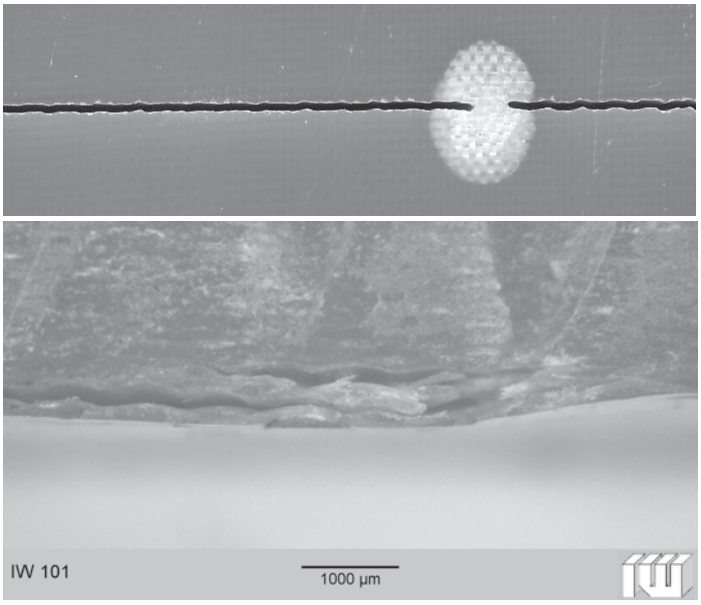

Fig. 1. *Macro- and microscopic views of the delamination on the glass fibre/epoxy-resin composite surface*

It may cause variable but serious damage to a material, usually containing several to several tens of square millimetres of area, including one or more layers of laminate. Further propagation of the delamination does not proceed spontaneously. However, when the material is subjected to a loading under working conditions the properties of the material may deteriorate and the structure in which it is used may fail (for instance, the buckling of a construction [8]). In the worst case the element may be completely destroyed. For this reason the degree of delamination of a material should be considered as a critical criterion determining the technological quality of the production of elements from a fibrous composite material. It can be assumed that there are two main reasons for the delamination during the cutting of laminar fibrous composite materials when using the abrasive water-jet:

1) those due to the properties of a material, which are the consequences of inhomogeneity, caused by incorrect or uncontrolled manufacturing processes or damage to the fibrous mat during its production (knots, fluff),
2) those caused by the cutting process itself, due to the inherent instability of the abrasive water-jet, being a liquid.

This may also be connected to instantaneous irregularities in the amount of abrasive material supplied. The supply of abrasives is mainly reliant on the systems feeding the abrasive material to the cutting head and on the inhomogeneity of the abrasive material (its density, shape and grain size).

Taking into account the serious technical and financial consequences of damaging composite materials by delamination, the introduction of systems monitoring its occurrence, its extent and the identification of damaged areas along the cutting line should be considered at an initial stage of the machining. In the rather meagre literature on this subject the problem of delamination by water-jet cutting or the possibility of monitoring the phenomenon do not appear to have been addressed.

2 CONCEPT OF THE MONITORING SYSTEM OF THE GLASS/EPOXY COMPOSITE DELAMINATION PROCESS

The published results of experimental studies on abrasive water-jet cutting, obtained with the use of various types of measuring sensors, have not dealt with the question of delamination and have focused mainly on two areas of investigation:

– diagnosis of the rate of wear of the cutting nozzles, using microphones or hydrophones ([9] to [11]),
– recognition of the state of complete or incomplete cutting or boring the material, using microphones, hydrophones, vibration sensors or acoustic emission sensors ([11] to [14]).

These studies have shown that this type of diagnostic methodology can be highly effective in

selected applications. This is important where direct control of the process is not possible, for example when working underwater. The literature describes attempts to diagnose cutting with an abrasive water-jet based on physical processes during:
– the formation of the abrasive water-jet,
– the removal of material during cutting.

These are:
– the level of the sound generated in the cutting head and during the interaction of the abrasive water-jet with the surrounding air and the material being machined,
– vibrations within the workpiece, caused by the impact of water droplets and abrasive particles, the pulsation of the water supply, the varying quantities of the supplied abrasive material and the cyclic character of the material removal process,
– the emission of an acoustic wave, due to the micro-cutting, material erosion, formation of micro-fractures and splitting within the worked material.

The process of cutting composite materials is accompanied by analogous physical processes. Additionally, the literature describes measurements of acoustic emissions carried out during the tests of the mechanical strength of the composite materials being considered, which have led to the conclusion that the processes of fracturing of the fibres and their being pulled out of the woven mat, as well as the tearing off of adjacent layers of a laminate during delamination, may also be a useful investigation source in the form of acoustic emission signals [15]. Therefore, a monitoring system based on vibration sensors, acoustic-emission detectors and microphones should be considered. To analyse the usefulness of particular sensors it is proposed that an analysis of collected signals be made in the time and frequency domains.

3 EXPERIMENTAL RESEARCH

3.1 Experimental setup

Preliminary studies had been carried out on glass-fibre/epoxy-resin laminated plates, containing 63% fibres. The investigations were carried out under the following conditions:
– water pressure: 300 MPa,
– abrasive mass-flow rate: 6 g/s,
– type and size of the abrasive: garnet 80 mesh,
– diameter combination of the water nozzle and the mixing nozzle: 0.3/0.8 mm,
– cutting without immersion of the element,
– thickness of samples: 10 mm, 20 mm.

The signals from two sensor groups were studied during this phase to evaluate the usefulness of the signal:
– contact sensors:
a) vibration sensor (accelerometer) Brüel&Kjær 8309,
b) acoustic emission sensor Brüel&Kjær 8313,
– non-contact sensor:
a) hydrophone Brüel&Kjær 8103.

The sample was cut towards the mounted sensors so the measuring distance diminished over time. A diagram of the test setup is shown in Figure 2.

One of the reasons for the delamination of the composite material being cut with the abrasive water-jet was assumed to be a lack of uniformity in the feed rate of the abrasive material. Therefore, to simulate a realistic situation for the delamination of samples and to evaluate the effectiveness of delamination recording by individual sensors during the studies, disturbances or irregularities in the supply of the abrasive material were introduced. This was achieved by modifying the abrasive supply system so that the supply of abrasives to the cutting head could be interrupted for programmed intervals.

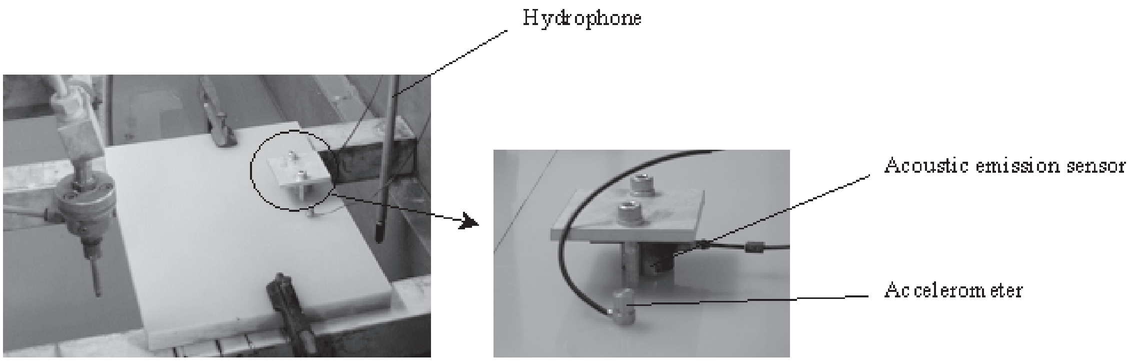

Fig. 2. *Experimental setup for the diagnosis of the delamination process*

The signals generated by the sensors were collected, translated and sampled by the data-acquisition plate, and afterwards analysed using specialised software. The acoustic-emission signal was sampled at 700 kHz, and the signals of the vibrations and the sound level were analysed at 200 kHz. The signal analysis was carried out on the basis of time and frequency. The following characteristic parameters were chosen to describe a signal:

– in the time domain: the signal amplitude, variance and kurtosis,
– in the frequency domain: the time-frequency spectrum (STFT spectrogram).

Variance contains information about the average divergence of a signal from its average value and it is a measure of the dynamics of signal energy [16]. Kurtosis shows the shape of the curve of the density of probability and is used for showing the

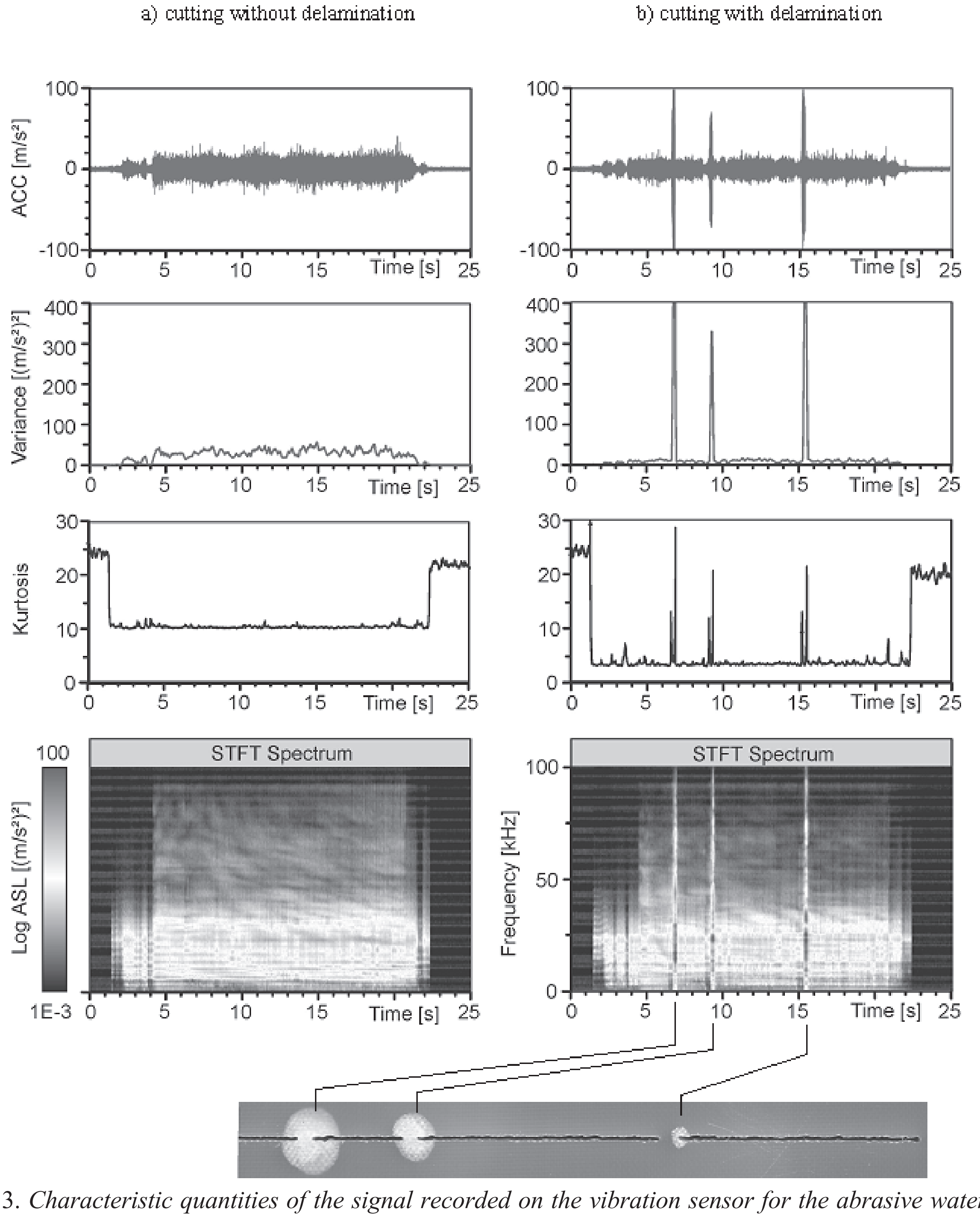

Fig. 3. *Characteristic quantities of the signal recorded on the vibration sensor for the abrasive water-jet cutting: a) cutting without delaminations b) cutting with delaminations. Composite material thickness – 20 mm, v = 500 mm/min.*

shortwave components of a signal, the so-called "peaks". The STFT spectrogram shows, on the other hand, which part of a signal is contained in a chosen frequency band within a selected time interval [17].

3.2 Results

During the investigation, interruptions in the supply of abrasive material longer than 1 second were introduced. The aim of these tests was to find whether the selected sensors could differentiate a stable cutting from a disturbed state, causing the extensive delamination. Figure 3 shows a sample set of time-based emissions, statistical indices and the time-frequency spectra for both states, for the signal registered by the sensor of vibrations. In a stable mode the time signal contains no high-amplitude disturbances and the kurtosis and variance are free from peaks (see Figure 3a). In the time-frequency spectrum there are also no peaks, except in the broad band corresponding to the stable process of removal of the material. On the other hand, in the time signal with introduced disturbances the sections of signal corresponding to the delamination of the composite are easy to identify, due to the very high amplitude values (see Figure 3b). Similarly, the characteristic symptoms of delamination can be observed via changes in the acoustic emission signal (Figure 4b). Using STFT spectra of the vibration sig-

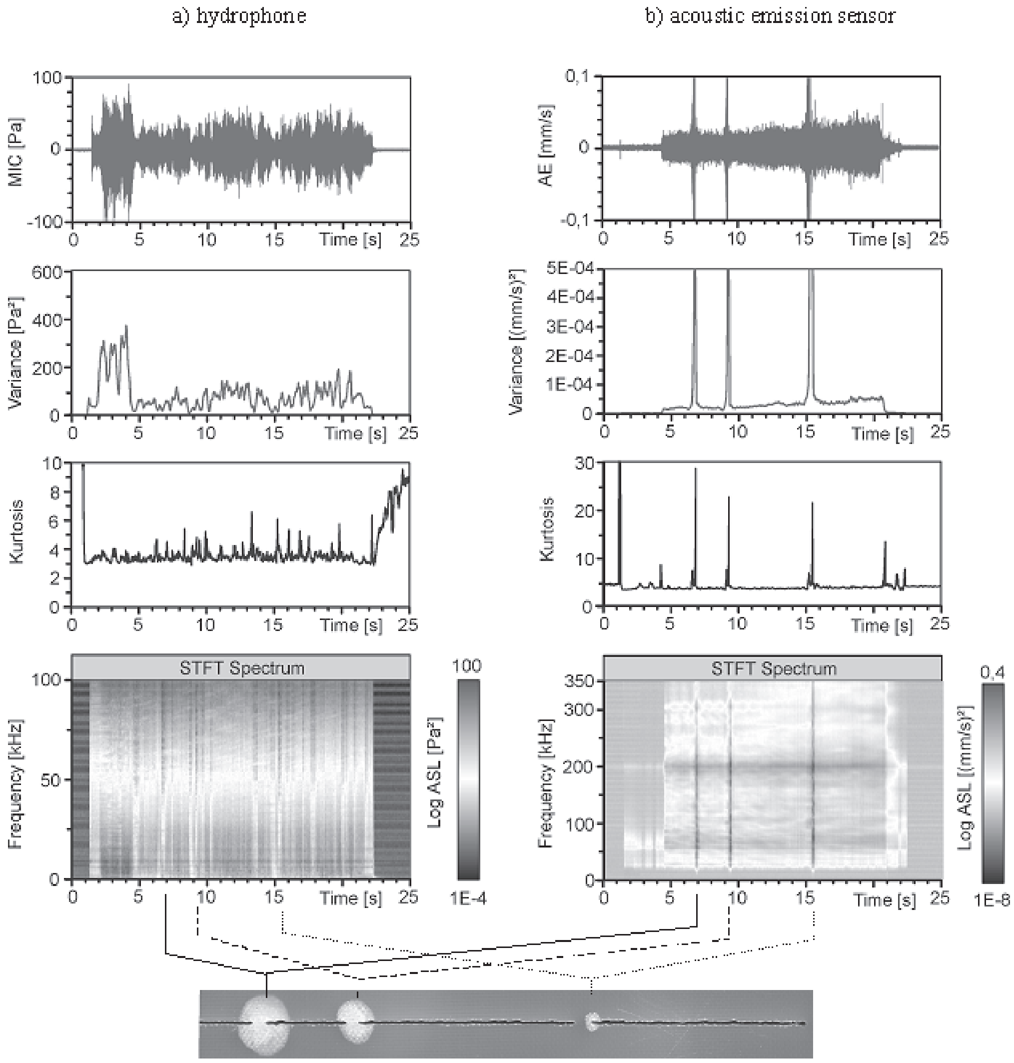

Fig. 4. *Characteristic quantities of the signal recorded for the abrasive water-jet cutting with delaminations: a) signal from the hydrophone b) signal from the acoustic emission sensor. Composite material thickness – 20 mm, v = 500 mm/min.*

nals of the acoustic emissions it would appear that the process of the loss of the coherence of inter-laminate layers cannot be ascribed only to one frequency or a defined frequency band. During delamination the sensors registered signals in the form of short, very intense peaks over the whole measured frequency range. The applied methods of signal analysis did not appear to be very effective for getting useful information from a hydrophone signal (see Figure 4a). This may be ascribed to the high level of background noise, particularly the high level of acoustic pressure generated by the friction of the sound generated by the abrasive water-jet passing through the successive air layers impinging on the hydrophone signal.

4 CONCLUSIONS

The obtained results prove that it is possible to monitor the delamination process for a composite thickness in the range 10 to 20 mm as it is cut with an abrasive water-jet. The purpose of this test is to detect delamination and its position along the line of the cut. During the tests it was found that hydrophones were not particularly useful in signal analysis. Conversely, very good identification of the delaminations of composites using vibration and acoustic-emission sensors was obtained. The presented analysis of the signals shows that delamination is a sudden process that cannot be predicted early enough to prevent it from happening. However, the obtained results create the basis for the automation of diagnostic procedures.

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