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Prediction system of surface damage

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Abstract – During laser cleaning, surface damage on the substrate could easily occur by overexposure to a laser pulse of high fluence. The damage is especially serious in art conservation where recently the laser has found a successful field of application. Successful cleaning without surface damage can be achieved by skilled expert operators with long experience and good technique. This paper presents a fuzzy rule-based expert system to predict surface damage during laser cleaning like a human expert. In this work, a fuzzy rule base was used to embed the acoustic information including an indication for the progress in cleaning and the result. An inference process was conducted to predict whether and how much surface damage would be induced on the substrate. In order to detect the acoustic waves a wide-band microphone was utilised. Tests of the performance of the fuzzy expert system showed that the prediction of surface damage is well correlated with the actual results independent of initial surface conditions. Finally, a process control algorithm for laser cleaning has been developed on the basis of the surface damage prediction system. © 2000 Éditions scientifiques et médicales Elsevier SAS

Keywords: laser cleaning / surface damage / fuzzy rule-based expert system / acoustic information / process control algorithm

1. Introduction

Laser cleaning is a complex phenomenon, which makes modelling by mathematical techniques difficult [1–5]. The processing itself is also delicate work needing much experience with empirical and intuitive feeling.

It is most important for the laser cleaning operator to avoid surface damage during cleaning especially for art conservation because surface damage could easily be induced on the invaluable object by overexposure to a laser pulse of high fluence. Successful cleaning without damage is only possible for experts with considerable experience and a skilful technique. In general, these experts are very sensitive to the snapping sound which is audible during laser cleaning. That sound is due to acoustic shock waves induced by the interaction between laser pulse and surface particles [6–8]. It has been reported that the acoustic emissions during laser cleaning are closely related to the surface condition and it is used to monitor and characterise the cleaning process [9–11]. Most expert operators conduct the laser cleaning successfully by being alert to these sounds. For example, if the expert operator recognises the sound as being too intense, i.e. laser fluence is high enough to cause a surface damage he should increase the laser working distance to reduce the laser fluence. The operator can also recognise when the cleaning has been finished and how far the cleaning has progressed from the change in intensity of these sounds with time. In summary, it may be known by listening to the laser cleaning process that acoustic intensity and the change in acoustic intensity with laser pulses provides an indication for the progress in cleaning and the result. As a result, surface damage can be predicted beforehand, quantitatively, by using the acoustic information.

In this paper, a fuzzy rule-based expert system is presented for predicting surface damage during the laser cleaning process like a human expert. The

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microphone as an acoustic sensor was used to make inputs to this system. The acoustic knowledge relating surface damage to acoustic intensity and change in acoustic intensity to laser pulses was embedded as a fuzzy rule base after analysing the acoustic signals. The fuzzy inference process using Mamdani's method [12], which is one of the direct reasoning methods, was conducted to produce the prediction value of surface damage during the process. Test results for implementing the fuzzy expert system as well as a brief discussion of the performance of this system are presented. An algorithm is developed to control the laser cleaning process.

2. Theoretical basis

In the laser cleaning process, experts are very sensitive to sound, i.e. the acoustic shock wave emitted from the surface under laser irradiation. That means that the acoustic waves have much information on the surface condition and cleaning progress. Therefore, it was attempted to exploit the acoustic information to predict the surface damage through the fuzzy expert system like a human expert. This system can also be applied easily for free damage control of the laser cleaning process.

To compare the sounds from two cases, i.e. one causing surface damage and the other not causing surface damage, two sequences of acoustic waves were analysed after detection using a microphone placed 10 cm from the interaction zone. *Figure 1* shows the acoustic intensity as a function of the number of laser pulses with two laser fluences, 1.5 and 2.7 J/cm^2 at the wavelength 1 064 nm. The specimen was toner paper on which laser pulses had been irradiated one by one. When the laser beam with a fluence of 1.5 J/cm^2 was irradiated on the paper the toner on the surface was removed clearly after the irradiation of the 6th laser pulse without surface damage. When 2.7 J/cm^2 laser pulse was applied severe surface damage was induced on the substrate following the 4th laser pulse. It is shown in *figure 1* that the acoustic feature of the laser pulses is obviously different with the two laser fluences. From this graph, it is also possible to say that initial acoustic intensity (sound intensity) and the change in acoustic intensity with laser pulses (sound change with time) give a clear indication whether surface damage would happen or not by overexposure to a laser pulse of high fluence.

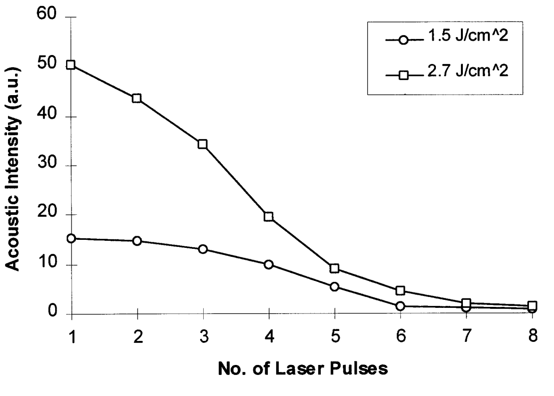

Figure 1. Acoustic intensity as a function of the number *f* of laser pulses with two laser fluences, 1.5 and 2.7 J/cm^2, on a paper surface contaminated with toner.

Therefore these two factors were selected for inputs to the fuzzy expert system to predict a surface damage during the laser cleaning process.

3. System and experimental description

A Q-switched Nd:YAG laser with a pulse length of 10 ns is used for the laser cleaning of toner paper which was simply prepared from the photocopy machine. In order to detect the acoustic waves induced by laser irradiation, a wide-band microphone (10 Hz–15 kHz) and the PC-based data acquisition and processing system were utilised. The distance between the microphone and the laser spot was around 10 cm.

The acoustic intensity (AI) for fuzzy system input resulted from the following procedure. Acoustic signals were sensed by the microphone, after which the signals were digitised (with the sampling rate of 50 kHz), filtered and fast Fourier transformed in the computer. The acoustic intensity (AI) was obtained by averaging the magnitude of the resultant frequency power spectrum at a valid frequency range (4–11 kHz). However, note that the mere intensity of an acoustic wave such as the RMS value can also be used in a more straightforward way. The amount of change in acoustic intensity (ΔAI) was also obtained by calculating the difference of current AI and previous AI. As a result, AI and ΔAI were used for inputs of the fuzzy expert system.

Figure 2 shows a block diagram of the experimental procedure for the prediction of surface damage using the fuzzy expert system.

3.1. Definition of the fuzzy input/output variables

In the fuzzy expert system, the acoustic intensity (AI) and the change in the acoustic intensity (ΔAI)

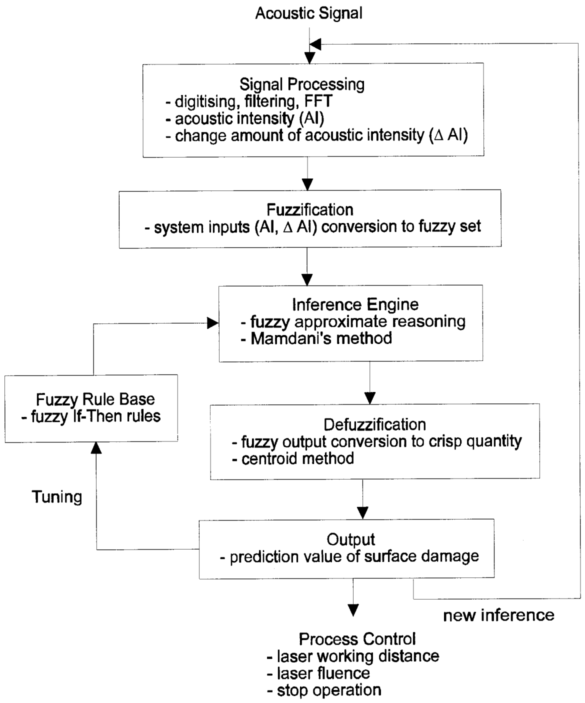

Figure 2. Block diagram of the experimental procedure for the prediction of surface damage using the fuzzy expert system.

were used as input variables. The combination of these variables were used to predict the surface damage (SD) during the laser cleaning process which was used as the output variable.

3.2. Fuzzification of the selected variables

The system input/output variables have a numerical value which must be correlated to a linguistic value. This was obtained through the design of membership functions consisting of a set of fuzzy set values. *Figure 3* shows the fuzzification of each fuzzy variable where the membership functions of all the variables used in this system were the triangular type.

3.3. Design of the rule base with the fuzzified variables

The fuzzy rules consist of the linguistic representation of the relationships between the input variables (AI, ΔAI) and the output variable (SD). Some of the most obvious rules can be easily rationalised from *figure 1.* At the ideal laser cleaning condition without surface damage, the AI has been observed at the linguistic value of small and ΔAI also decreases within a small range. We can then compose the fuzzy rule for good cleaning without damage as:

IF AI is small and ΔAI is small THEN SD is zero

When the laser fluence is too high surface damage can be severely induced. In this case the AI is very large and ΔAI is also large. Then, the rule can be written as:

IF AI is very large and ΔAI is large THEN SD is large

As a result, the total set of 15 fuzzy rules (5 AI fuzzy sets × 3 ΔAI fuzzy sets) was formed. It is also

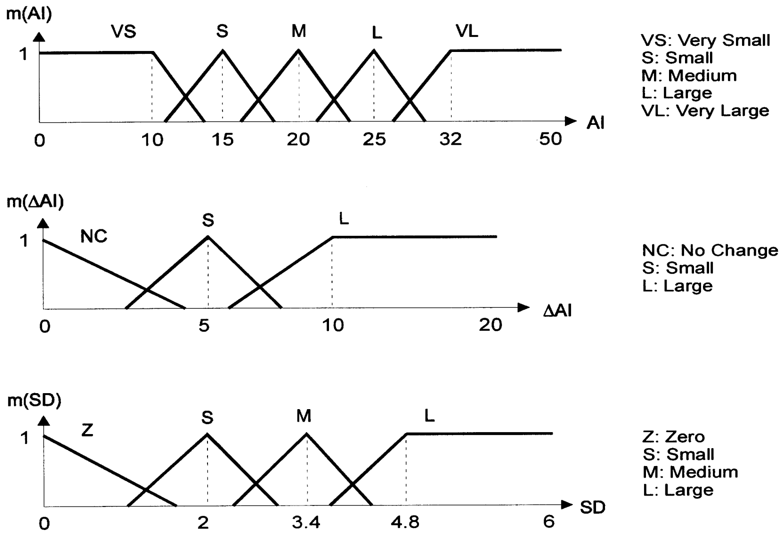

Figure 3. Membership functions for the system input variables (AI, ΔAI) and output variable (SD).

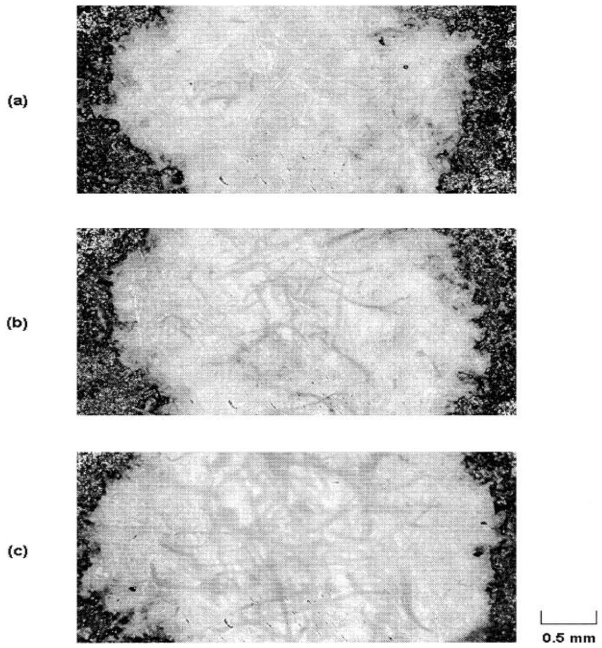

Figure 4. Laser-cleaned areas on a surface heavily contaminated with toner obtained after the irradiation of the 7th laser pulse with a laser fluence of: a) 1.5 J/cm^2; b) 2.1 J/cm^2; c) 2.7 J/cm^2.

noted that the optimum fuzzy rules should be carefully found through the knowledge of an expert operator as well as investigation of the experimental acoustic data since effect on the system's response by modifying the rules is very drastic.

3.4. Inference with the rule base

To derive the results of inference, the Mamdani's Min-Max method was used. Consequently, the value of fuzzified output could be presented as the following:

$$m_{SD'}(z) = m_{AI}(x) \ \wedge \ m_{\Delta AI}(y) \ \wedge \ m_{SD}(z)$$

$$m_{SD}(z) = m_{SD'1}(z) \ \vee \ \dots \ \vee \ m_{SD'n}(z)$$

where x and y are input singleton fuzzy sets and z is an output fuzzy set. n is the total number of fuzzy rules and $\wedge$, $\vee$ are Min and Max operators, respectively. $m_{SD}(z)$ is the resultant membership function of inference.

3.5. Defuzzification of the fuzzified output variable

For the defuzzification of the surface damage (SD), the centroid method to obtain a weighted average of the output membership function was used as follows:

$$SD^* = \frac{\int m_{SD}(z)\, z\, \mathrm{d}z}{\int m_{SD}(z)\, \mathrm{d}z}$$

The value of the SD^* was used as a measure of the magnitude of the surface damage.

The fuzzy rule-based expert system was developed using C-language on a PC and then performance test of this system was performed by the fuzzy program.

4. Results and discussion

4.1. Experimental classification of surface damage

In order to test the performance of the fuzzy expert system for predicting surface damage during laser cleaning, three laser fluences (1.5, 2.1 and 2.7 J/cm^2) were selected for classifying the output fuzzy sets of surface damage (SD) experimentally.

The laser-cleaned areas on a paper surface heavily contaminated with toner at the laser fluences of 1.5, 2.1 and 2.7 J/cm^2 are shown in *figure 4*. These areas were obtained after the irradiation of the 7th laser pulse on the same surface location. When the laser fluence of 1.5 J/cm^2 was applied for the cleaning, a well-cleaned surface without any evidence of surface damage on the substrate was achieved, which is shown in *figure 4a*. It can be then defined that the laser fluence of 1.5 J/cm^2 should correspond to the 'Zero' fuzzy set of surface damage (SD) at the defined membership functions shown in *figure 3*. *Figure 4b* shows that surface damage such that the paper fibre was raised on the cleaned surface was induced when the laser fluence of 2.1 J/cm^2 was applied. This is caused by overexposure to the higher laser fluence. It is also defined that the laser fluence of 2.1 J/cm^2 should correspond to the 'Medium' fuzzy set of surface damage (SD) at the membership functions. In addition, when the laser fluence of 2.7 J/cm^2 was applied on the surface severe surface damage was produced so that a very rough surface was formed owing to the overexposure to a laser pulse of a very high fluence, which is shown in *figure 4c*. It is also defined that the laser fluence of 2.1 J/cm^2 should correspond to the 'Large' fuzzy set of surface damage (SD) at the membership functions (see *figure 3*).

4.2. Characterisation of acoustic data (AI, ΔAI)

The acoustic input data (AI, ΔAI) were obtained during laser irradiation on various surface conditions, i.e. heavy, mild, light contamination of paper surface and almost free toner surface, etc. A total of 37 acoustic data sets (AI, ΔAI) were achieved in which 16 data sets were with a laser fluence of 1.5 J/cm^2 and 12 and 9 data sets were with a laser fluence of 2.1 and 2.7 J/cm^2, respectively.

Figure 5 shows the acoustic intensity (AI) data detected during laser cleaning with the three laser fluences. It is shown that the data are not distributed uniformly so it is difficult to classify the data with the laser fluences only using the acoustic intensity (AI). This implies that the acoustic intensity not only depends on the laser fluence but also is strongly dependent on the surface condition. As a result, it can be seen that the prediction of surface damage is almost impossible to achieve with the acoustic intensity (AI) alone since it is too difficult to find differences between the laser fluences owing to the strong dependency on surface condition.

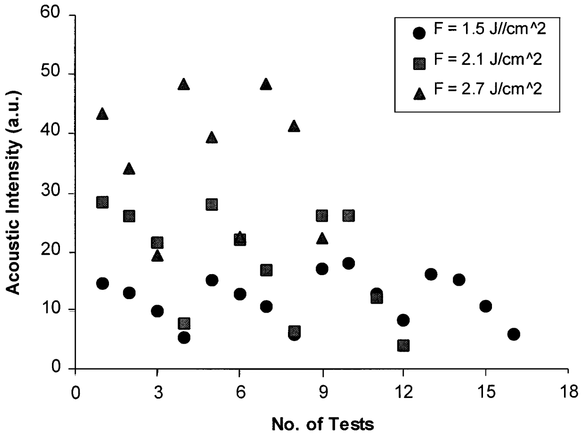

Figure 5. Acoustic intensity (AI) data detected in the three laser fluences.

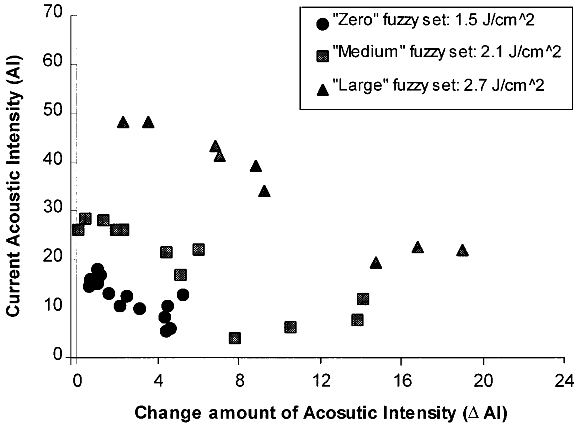

Figure 6. X–Y plot of two acoustic input data (AI, ΔAI) for the fuzzy expert system.

Figure 6 shows the plot on the x–y plane of two acoustic input data (AI, ΔAI) for the fuzzy system. It is shown that the data are uniformly distributed to some extent. The acoustic data obtained from the laser fluence of 1.5 J/cm^2 defined as representing the 'Zero' fuzzy set in surface damage (SD) (which was described in the previous section) are generally located in the region of low AI and low ΔAI while the data from the laser fluence of 2.7 J/cm^2 defined as representing the 'Large' fuzzy set in surface damage (SD) are located in the region of high AI and high ΔAI. This implies that the two types of acoustic data, AI and ΔAI, are reasonable inputs for the fuzzy system to predict the surface damage.

4.3. Performance test of the fuzzy system

A total of 37 acoustic data sets was used to test the performance of the fuzzy system. The data set was formed by detecting the initial two acoustic waves induced by the irradiation of the first and the second laser pulses.

Figure 7 shows the test results of the fuzzy system for predicting surface damage. When the laser fluence of 1.5 J/cm^2 was used, the range of the predicted value of surface damage was 0.47–1.56.

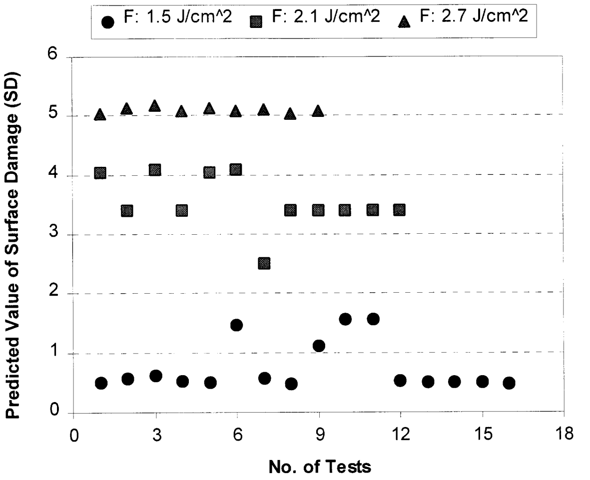

Figure 7. Test results of the fuzzy expert system for predicting surface damage.

This range includes mainly 'Zero' fuzzy sets and very partially 'Small' fuzzy sets of the surface damage (SD) at pre-defined membership functions (see *figure 3*). When the laser fluence of 2.1 J/cm^2 was applied, the range of the predicted value of surface damage was 2.40–4.08. The range includes mainly 'Medium' fuzzy sets and partially 'Large', 'Small' fuzzy sets of the surface damage (SD) at the output membership functions. Similarly when the laser fluence of 2.7 J/cm^2 was applied, the range of the predicted value of surface damage was 5.03–5.17. The range belongs totally to 'Large' fuzzy sets of the surface damage (SD) at the output membership functions (see *figure 3*). From the results, it can be seen generally that the prediction values from the fuzzy system agree well with the fuzzy set of surface damage (SD) pre-defined from the observation of the results of substrate surface after cleaning. It is also shown in *figure 7* that the system has responded consistently to the output without the effect of variation in surface conditions. This implies that the system could make a robust prediction for any surface condition on the substrate during the laser cleaning process.

4.4. Process control algorithm

Based on the surface damage prediction by the fuzzy rule-based expert system, an algorithm has been developed for the real-time process control of laser cleaning. *Figure 8* shows the flowchart of the algorithm. First, all substrate parameters such as material and dimensions are input into the fuzzy controller. Subsequently, the laser parameters such as wavelength, pulse length, pulse energy and spot size are inputted into the controller. The fuzzy con-

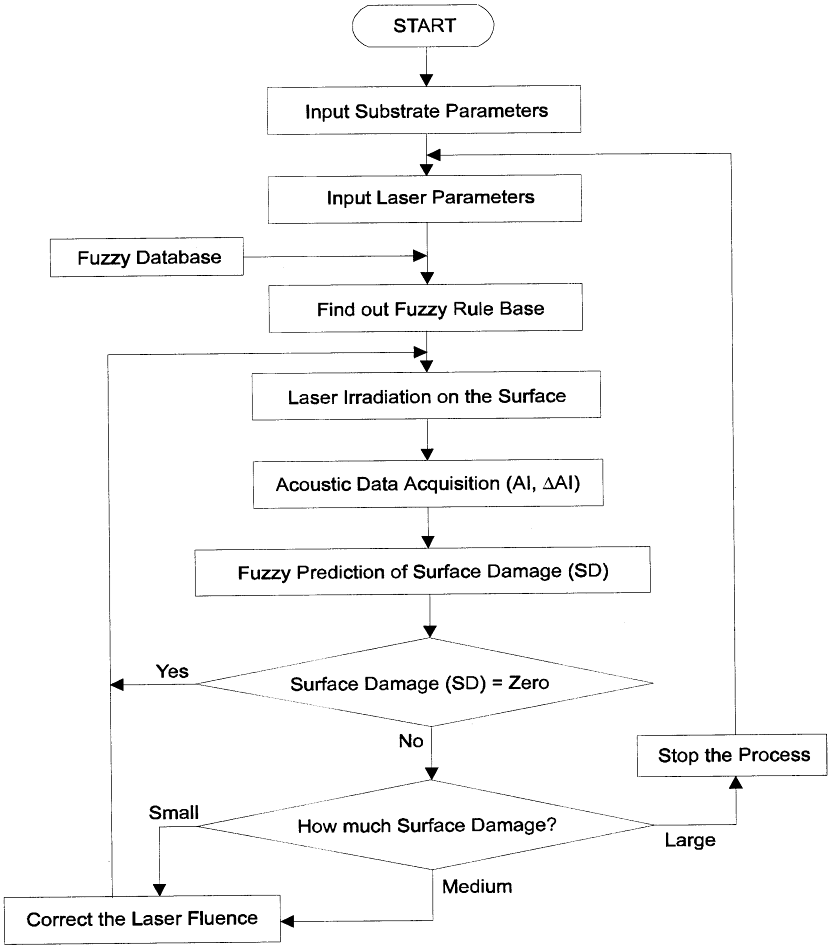

Figure 8. Flowchart of the real-time process control algorithm.

troller ascertains the appropriate fuzzy rule base related to the substrate and the laser parameters from the fuzzy database in which various fuzzy rules and membership functions of fuzzy sets have been accumulated through previous experiments. After retrieving a specific fuzzy rule base in the controller, the laser cleaning starts on the contaminated surface. At the same time, the controller detects the acoustic emission and performs the signal processing such as digitising, filtering and fast Fourier transforming to obtain the fuzzy acoustic input data (AI, ΔAI). A fuzzy inference is then carried out to achieve the prediction value of surface damage (SD) using the direct reasoning method (Mamdani's Min-Max method). If the prediction value belongs to the 'Zero' output fuzzy set then further laser irradiation is permitted to clean the surface continuously. On the other hand, if the prediction value for surface damage is high enough to induce surface damage on the substrate (i.e. the value belongs to the 'Small' or 'Medium' or 'Large' output fuzzy sets), the control actions are followed. If the output value is sufficiently high enough to cause severe surface damage (in which case the value might belong to the 'Large' output fuzzy set) the cleaning process should be stopped immediately to avoid the predicted disaster on the substrate and then the initial laser parameters should be re-selected. Meanwhile, if the output value is relatively low (i.e. the value might belong to the 'Small', or 'Medium' output fuzzy sets) the laser fluence is tuned by changing the pulse energy or laser working distance using the pre-defined relationship between the output fuzzy set and the laser fluence. Then, the laser cleaning process continues following the correction of laser fluence.

As a result, this algorithm provides a scheme not only to avoid surface damage to a substrate in advance but also to control the cleaning process efficiently by changing the laser parameters during the process. In addition, if we use process control factors such as laser working distance and laser pulse energy as an output of the fuzzy system instead of the surface damage (SD), the system can be used directly for the control of the laser cleaning process.

5. Conclusions

In this paper, a fuzzy rule-based expert system was developed in order to predict surface damage during the laser cleaning process like a human expert cleaner. From the investigation of the expert behaviour and the experimental acoustic data, an optimum fuzzy rule set of 15 rules has been achieved for the prediction system. Based on the 15 fuzzy rules, it was seen from the performance tests that the prediction of surface damage has been successfully conducted by the resultant fuzzy rule-based expert system. The system also responded consistently to the output without the effect of variation in surface conditions. Based on the surface prediction by the fuzzy rule-based expert system, a process control algorithm has been developed. The algorithm provides a scheme to avoid surface damage to a substrate in advance as well as to control the cleaning process efficiently by changing the laser parameters during the process.

References

[1] Watkins K.G., A review of materials interaction during laser cleaning in art restoration, in: Kautek W., König E. (Eds.), Lasers in the Conservation of Artworks (LACONA I), Restauratorenblätter (Special Issue), Mayer & Comp., Vienna, 1997, pp. 7–15.

[2] Russo R.E., Laser Ablation, Appl. Spectrosc. 49 (1995) 14A–28A.

[3] Lu Y.F., Aoyagi Y., Takai M., Namba S., Laser surface cleaning in air: mechanisms and applications, Jpn. J. Appl. Phys. 33 (1994) 7138–7143.

[4] Myamoto I., Ooie T., Hirota Y., Maruo H., Mechanism of laser ablation: ablation process and debris formation, in: Proceeding of ICALEO'93, Laser Institute of America, San Diego, USA, 1993, pp. 1–10.

[5] Asmus J.F., Light cleaning: laser technology for surface preparation in arts, Technol. Conserv. 3 (1978) 14–18.

[6] Fairand B.P., Clauer A.H., Laser generation of high-amplitude stress waves in materials, J. Appl. Phys. 50 (1979) 1497–1502.

[7] Devaux D., Fabbro R. et al., Generation of shock waves by laser induced plasma in confined geometry, J. Appl. Phys. 74 (1993) 2268–2273.

[8] Peyre P., Fabbro R., Laser shock processing: a review of the physics and applications, Optical and Quantum Electronics 27 (1995) 1213–1229.

[9] Lee J.M., Watkins K.G., Real-time surface monitoring in the laser cleaning of copper for soldering processes, Lasers Eng. 8 (1999) 229–239.

[10] Lu Y.F., Aoyagi Y., Acoustic emission in laser surface cleaning for real-time monitoring, Jpn. J. Appl. Phys. 34, Part 2 (1995) L1557–L1560.

[11] Cooper M.I., Emmony D.C., Larson J.H., Characterisation of laser cleaning of limestone, Optics Laser Technol. 27 (1995) 69–73.

[12] Mamdani E.H., Application of fuzzy algorithms for control of simple dynamic plant, Proc. IEE 121 (1974) 1585–1588.