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A Virtual Laboratory for Laser Transformation Hardening*

A. GARCÍA-BELTRÁN, J. L. OCAÑA, C. MOLPECERES, M. MORALES, J. M. GONZÁLEZ, M. BLASCO and D. IORDACHESCU
Centro Láser—Universidad Politécnica de Madrid, Ctra. de Valencia, km. 7, 3, Campus Sur U.P.M. (Edificio 'La Arboleda'), 28031 Madrid, Spain. E-mail: agarcia@etsii.upm.es

The main purpose of this work is to describe the fundamentals and application of a web-based virtual laboratory as a facility to assist undergraduate students of engineering to learn industrial laser applications and to practice laser procedures techniques. Furthermore, this paper presents the pedagogical methodology and the results drawn from this experience. The system helps students to perform laser hardenings of steel and to examine results immediately. Students only need a computer connected to the Internet and a web browser in order to take advantage of all the application functions. The system architecture, the graphic user interface design and an on-line help system eases user interaction with the system.

Keywords: virtual laboratory; web-based system; learning-teaching strategies; laser transformation hardening

1. Introduction

Simulators and virtual laboratories have been used in for training in many fields such as science and engineering [1–3]. The aim of this work is the development of a virtual laboratory of laser industrial applications. Laser technology leads to implement many industrial processes (cutting, welding, marking, transformation hardening . . .) with better results than traditional methods, easy to control and saving time and resources [4]. One of the advantages of this technology is the possibility to use the same laser system to do different processes with the suitable set up of the process parameters (laser power intensity, interaction time . . .) [5]. For instance, in the case of a deep penetration welding in steel you have to obtain enough temperature to get plasma states whereas for transformation hardening you have to avoid to reach melting temperatures in the material surface. In this way the determination of the right values of the parameters of each specific processes one of the fundamentals in the technical staff training in laser application industries or investigation centers. High power laser laboratories usually contain rather expensive equipment. The possibility to employ virtual laboratories in order to make easy the technical staff training can be very advantageous with the purpose of the reduction of time, resources and training costs. If these virtual laboratories are web-based systems the advantage elevates these characteristics to their highest levels due to time-space restrictions removing and also can make easy the collaboration in the technical training among international laser technology organizations.

The LASTED.net Consortium (*LASerTechnolgy EDucational.network*) was supported by the Leonardo da Vinci Programme and involved the main European R+D institutions for industrial laser applications [6]. The general objective of this project is to improve the accessibility of training and widening the scope of specialised vocational training that can be offered and to exchange experiences regarding training programmes to deduce best practice. The specific aim of LASTED.net was the setup for a didactical experiment or simulation of a specific laser industrial application (cutting, welding, marking, micromachining, transformation hardening . . .) to be installed in each participating laboratory (Ljubljana, Vienna, Berlin, Odense, Marseille and Madrid). The parameters necessary to control the application must be made adjustable via web. Each virtual laboratory must include a general description of the experiment including the parameters required to determine the success and the resources necessary to sufficiently inform the user about the process and results. The main parameters for the success or failure have to be determined derived from the core didactical value and purpose of the experiment. The type of parameters to be set up can cover a wide range of aspects from a numerical value inside a certain range for some factor (i.e. spot diameter, speed and laser power) to a selection of materials. Anyway, at the core of the idea behind the experiment is the learning objective or didactical value.

The Centro Laser of the Universidad Politécnica de Madrid was founded in 1998 with the intention to establish a relationship between the industry and the university, and to promote the research, development and diffusion of the laser technology [7]. On

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the basis of the gathered experience in modelling, experimental characterisation and instrumentation for industrial applications of this tool, this institution offers its human and material resources to develop the laser technology in the ever increasing applications of this tool in several sectors. The Centro Laser as member of the LASTED.net Consortium, chose the transformation hardening of steel as the specific process to be implemented in a virtual laboratory.

The laser transformation hardening process and the developed virtual laboratory are presented at the beginning of this paper. Nowadays the application is used as a didactic resource in some courses of the Industrial Engineering degree and the Master in Laser Technology taught at the Escuela Técnica Superior de Ingenieros Industriales of the Universidad Politécnica de Madrid (ETSII-UPM). So, the rest of the paper describes its use in support of traditional instructional methods in a course taught in the Physics Department of the ETSII-UPM, by clearly indicating the initial objective, the procedure adopted, and the conclusions drawn from this experience.

2. Laser transformation hardening

Laser transformation hardening of ferrous materials is a process used to enhance the mechanical properties (wear resistance and also fatigue strength) of highly stressed machine parts, such as gears and bearings [8–10]. Increased hardness and strength are obtained by quenching a thin surface layer of the material from the austenite region to form hard martensite and leaving the interior of the work-piece essentially unaffected. Self-quenching occurs when the cold interior of the work-piece constitutes a sufficiently large heat sink to quench the hot surface by heat conduction to the interior at a rate high enough to allow martensite to form at the surface. A laser beam can generate very intense energy fluxes at the workpiece surface and is essentially independent of the workpiece, easily controlled, requires no vacuum and no contact and generates no combustion products.

When a laser beam incidents on a surface, part of its energy is absorbed as heat at the surface. If the power density of the laser beam is sufficiently high, heat will be generated at the surface at a rate higher than heat conduction to the interior can remove it, and the temperature in the surface layer will increase rapidly. In a very short time, a thin surface layer will have reached austenitizing temperatures, whereas the interior of the workpiece is still cool. Even with a relatively moderate power density of $500°W·cm^{-2}$, temperature gradients of $500°C·mm^{-1}$ can be obtained. By moving the laser beam over the workpiece surface, a point on the surface within the path of the beam is rapidly heated as the beam passes (Fig. 1). This area is subsequently cooled rapidly by heat conduction to the interior after the beam has passed. By selecting the correct power density and speed of the laser spot, the material will harden to the desired depth. The upper limit for the surface temperature in laser processing is set by the melting point of the material because surface melting is undesirable in most instances.

A lot of factors can influence the results of laser transformation hardening including size of the laser spot, power density, uniformity of power density, processing speed, thermal properties of the material, and laser hardenability of the material. For instance a relatively broad area beam, often in the shape of a square or a rectangle, is used in the laser hardening process. The power density of a focused laser beam used for hardening is much lower than the power density of the small, intense focused spots used for welding and cutting. The hardenability factor encompasses the material response to rapid heating and quenching and is, in part, dependent on the starting condition of the material, that is, whether the material is normalized, annealed, and so on.

Although the resulting depth of case will depend on the hardening response of the material, it will rarely be more than 2.5 mm. For steel with low hardenability, such as low and medium-carbon steel, the depth of case obtainable is much smaller, varying from 0.25 mm in mild steels to 1.3 mm in a medium-carbon steel [11]. Fig. 2 shows an

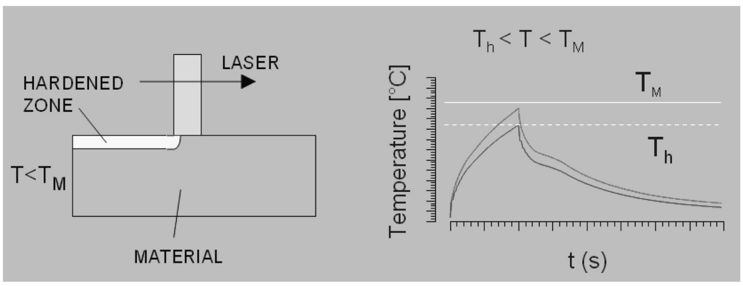

Fig. 1. Laser transformation hardening scheme and corresponding thermal cycles.

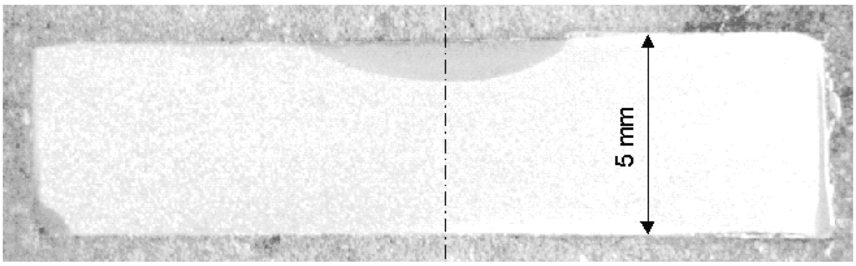

Fig. 2. Metallographic cross section of laser hardened steel sample irradiated with a CO_2 laser beam.

example of a carbon steel sample after the laser treatment.

The major advantages of laser surface hardening include: close control of the power input with metal-working lasers; the laser can provide high power density in selected areas, which in turn minimizes the total energy input, and thereby, dimensional distortion; and the ability of the laser to reach normally inaccessible areas on the workpiece surface. Because no vacuum or protective atmosphere enclosure is needed, and the distance from the workpiece to the last optical element of the laser system can be quite long, it is possible to process very large or irregular-shaped workpieces. The laser beam can also be optically shaped or split to accommodate different geometries.

3. The virtual laboratory description

The objective of the system is to determine the right values of the more important parameters of a transformation hardening of steel with a Nd:YAG laser system. The main process parameters are the laser power density (calculated by the laser power and the spot size) and the process speed (to determine the interaction time). It is obvious that processing speed should be as high as possible to attain high production rates. However, the speed at which the laser spot moves over the surface is not a good measure of the production rate by itself because the dimensions of the spot normal to the direction of travel are equally important in determining the area coverage rate. Another important factor in determining the results of processing is the dwell time. The relative dimensions of a rectangular spot do not influence the coverage rate as long as the power density stays constant. Therefore, the area of the laser spot that will give a specific result is limited by the available power. An exception to this is when the spot is very narrow in the direction of travel and/or when the speed is very low. Under such conditions, lateral heat losses become large and the spot dimensions influence the results. In our laboratory you can get experience in controlling a laser for surface hardening treatments of a mild steel and users will be able to select the values of the main parameters of the process: the power density, the beam diameter and the processing speed.

The whole simulator interactivity, based on a web-based arquitecture, is carried out by means of a web server and a computer connected to the Internet with a web browser [12]. The following free-software systems and programming tools have been employed by the development team: Ubuntu (Linux) operating system [13], Apache HTTP Server [14], MySQL date base management system [15] and PHP [16] and Javascript [17] script languages. The graphic user interface can be shown by any HTML 4.0 compatible web browser [18] and is designed to work with different screen size set up (800×600, 1024×768, 1152×864, 1280×1024 and 1600×1200).

The GUI is expected to be simple, clear and efficient, so all the information is gathered in a window split up into few areas as shown in Fig. 3.

APPLICATION HEADING		*PROCESS SELECTION TABS*
Cartoon character *area*	*Virtual process* ***instructions*** *and* ***qualitative results*** *area (textual information)*	***Images*** *and* ***video*** *results area (multimedia information)*
Transformation hardening tutorial link	***Control panel*** *area for selection of process parameters values*	*Button and icons area for* ***detailed results selection***

Fig. 3. Virtual laboratory GUI window organization.

Fig. 4. Welcome in the virtual laboratory interface.

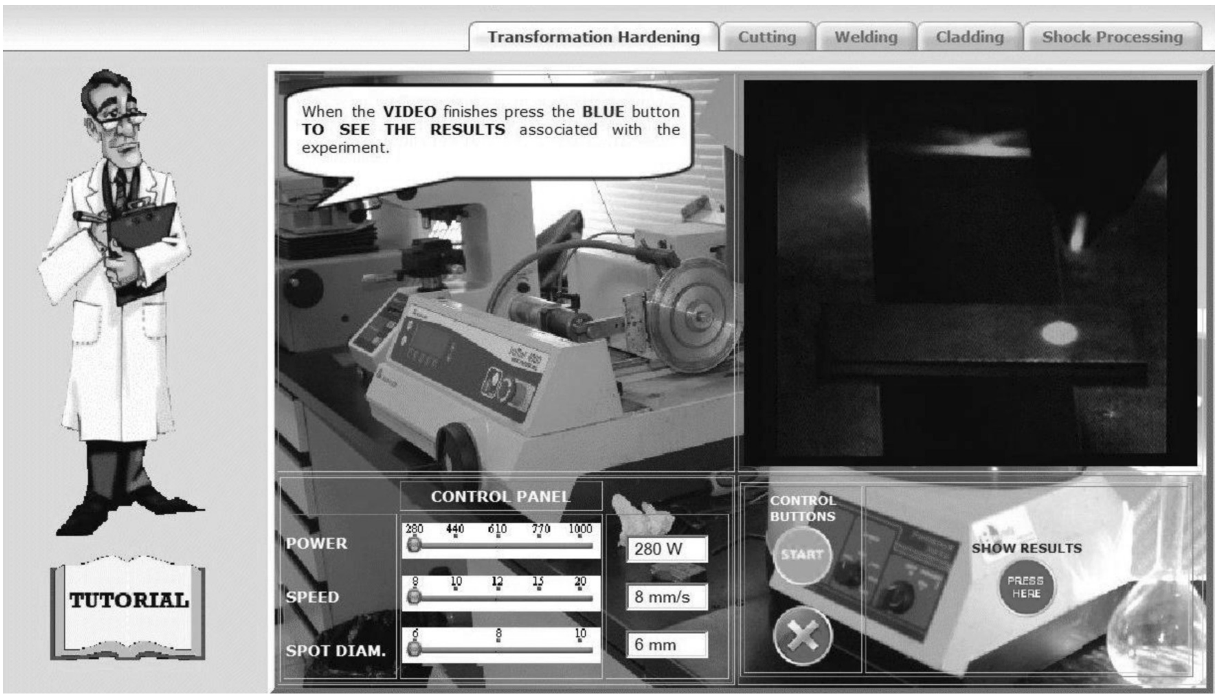

Fig. 5. The virtual laboratory interface: watching the process.

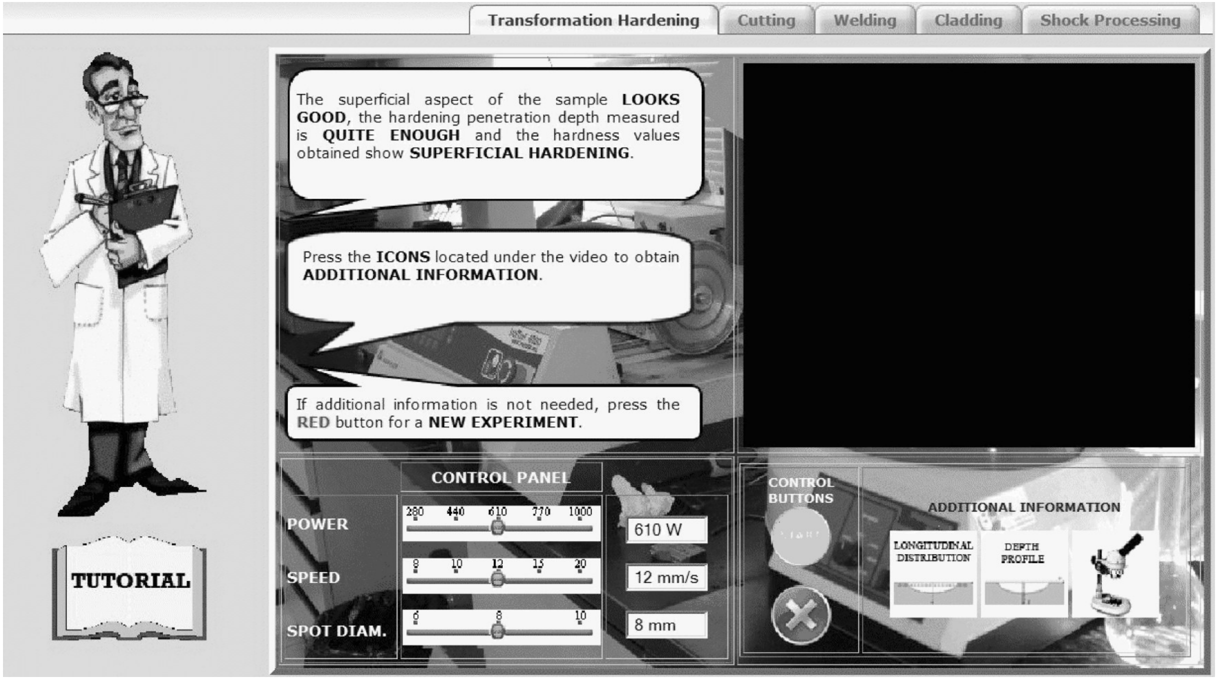

Fig. 6. The virtual laboratory interface: qualitative results.

The user can choose the system language (English or Spanish) before accessing the initial window interface. In this window the central area provides a short explanation about the experiment procedure (cartoon character balloon), whereas the button area let the user adjust the values for the three main process parameters: the laser power, the laser beam spot diameter and the laser beam speed by means of slider controls (Fig. 4). As said before the first two parameters set the power intensity and the last one establishes the interaction time over the material surface.

Once the values are chosen, the user can start the process (Start button) and watch the corresponding video (previously recorded and stored in the system database) in the right area like in real-time (Fig. 5). The video size is 352×288 so the time to download it from the server is reduced but the video quality is rather acceptable. The length of the corresponding process video is between 7 and 19 seconds depending on the laser speed. During playing the video the user can click over it to open a new full screen window in order to get a better view of the process. On the other hand clicking over the red cross button will stop the video play.

As soon as the process finish, the user can see the results and analyse them immediately. The application provides a results summary of the laser-material interaction with a first qualitative description of the outcome (balloon in Fig. 6) and suggests next steps to do.

Moreover when clicking over the blue button also facilitates more graphic feedback: the metallographic cross sections of the treated sample and surface micrographics (Fig. 7) of the material heat affected zone and the micro-hardness profiles (depth and transversal) in these material areas after the transformation hardening (Fig. 8). These data can evaluate quantitatively the goodness of the selected values for the process parameters.

Process effects depend on the values of the primary decisive process parameters. As these parameters are strongly interconnected it is easy to verify that there are several different values combinations to get similar results. In industrial applications shortest processing times or lowest laser power are wanted according to the circumstances. In general experiments can be classified in three groups depending on the laser system energy:

(a) process with insufficient energy: there is no hardened (heat affected) zone in the steel sample
(b) process with enough energy to obtain good results of transformation hardening.
(c) process with excessive energy: an undesirable surface melting in the steel sample is obtained.

To repeat the experiment the user must click over the red cross button and select the parameters values for the new process.

Furthermore the user can get additional information about laser transformation hardening with a link associated to the *Tutorial* text in the left button

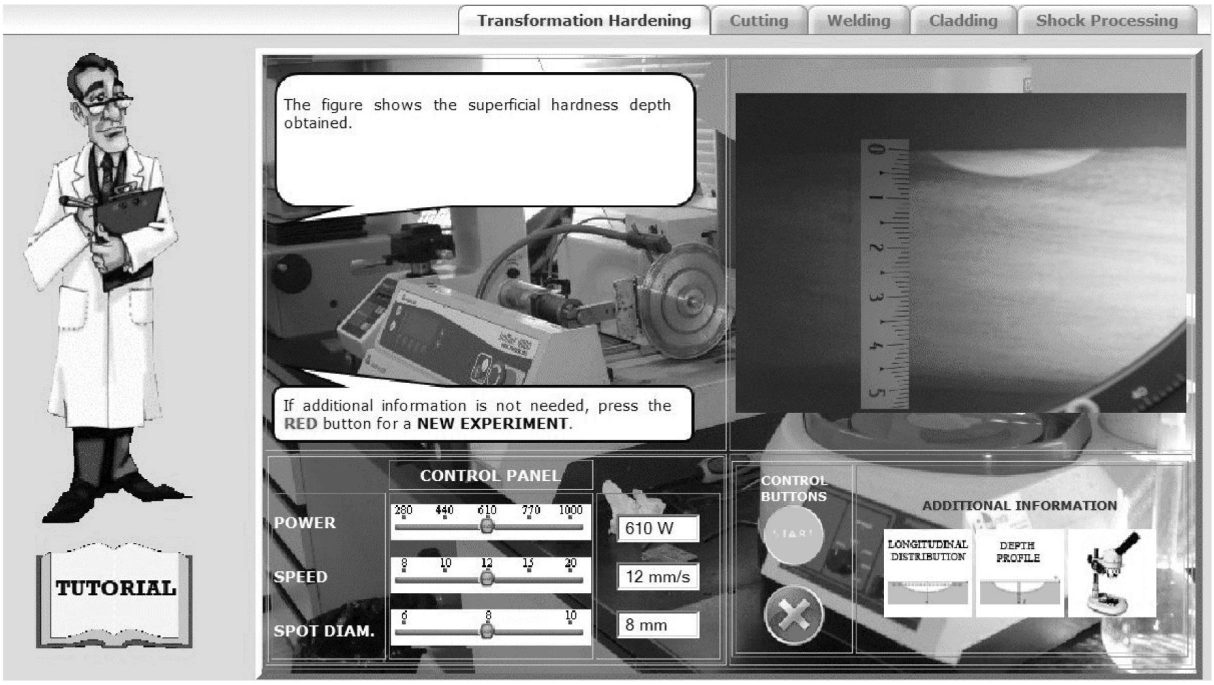

Fig. 7. The virtual laboratory interface: macrography showing the heat affected zone.

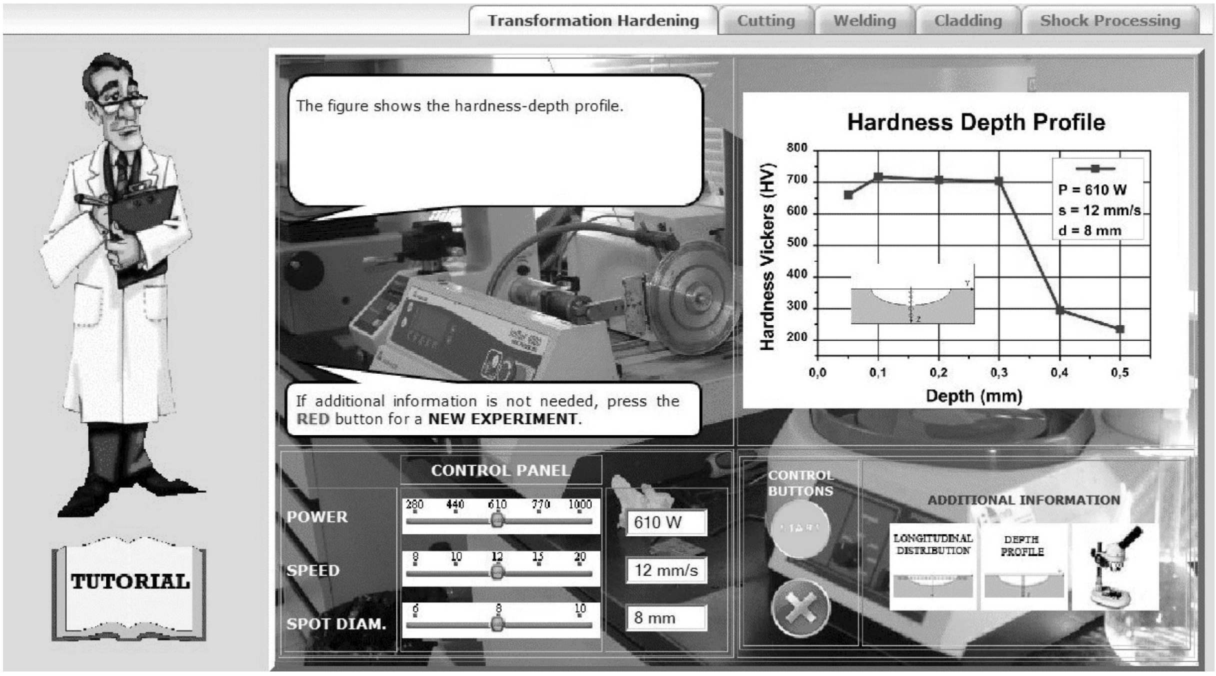

Fig. 8. The virtual laboratory interface: showing the microhardness profile.

area (Fig. 9). This tutorial can serve as a guideline for users and dissemination.

In order to implement the virtual procedure a database with 75 true experiments corresponding to all the combinations of the sets of values for the three process set up parameters has been previously created. The following equipment of the Centro Laser has been used for this experimental work: ROFIN-SINAR DY033 Nd:YAG laser system, ABB IRB 4400 robot system, Bosch video-recording system, several metallographic laboratory tools (dicing system, profile meter, polishing machine and microhardness tester) and C45E steel samples (size: $100 \times 50 \times 5$ mm).

The values are shown in Table 1 and let the user to specify a selection of parameters not only for accep-

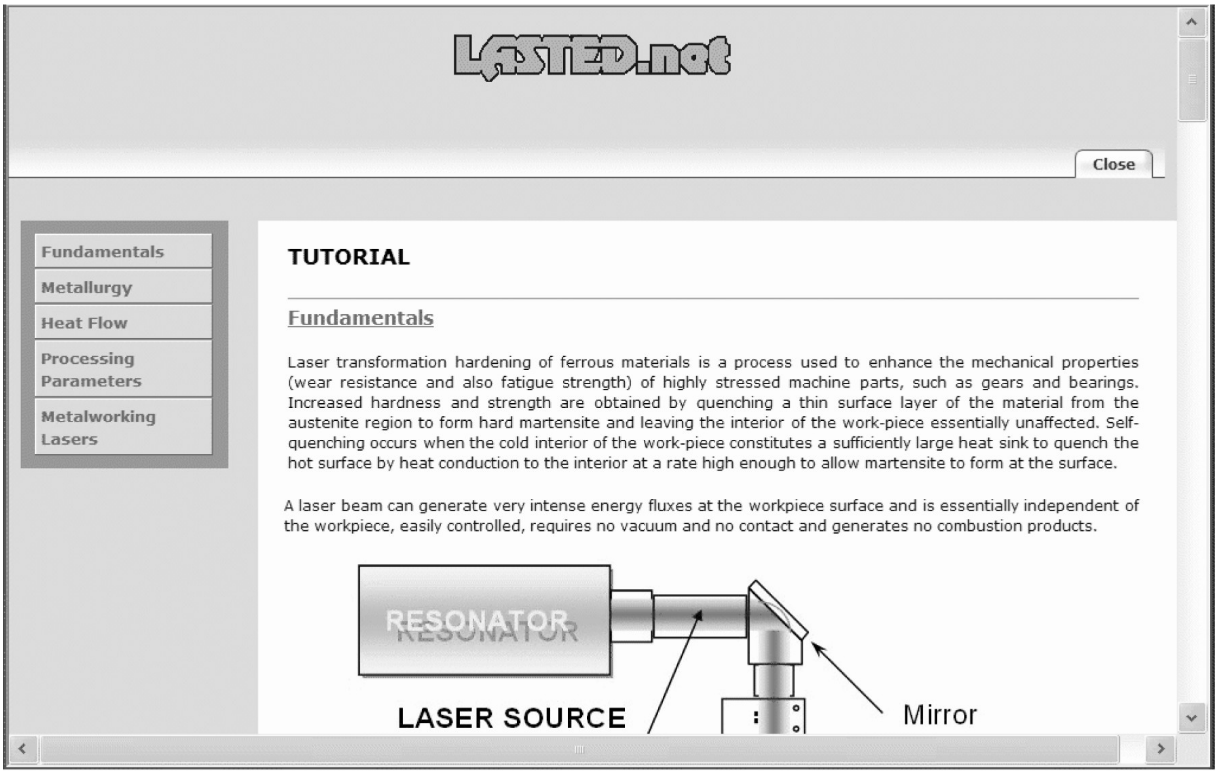

Fig. 9. The online tutorial of the laser transformation hardening of the virtual laboratory.

Table 1. Range of values for the three main process parameters

Process parameter	Values
Laser power (W)	280, 440, 610, 770, 1000
Laser beam diameter (mm)	6, 8, 10
Laser speed (mm s^{-1})	8, 10, 12, 15, 20

table process results but also for rejected ones. The database stores not only these values but also the corresponding process video and the qualitative and quantitative results.

4. Learning-teaching aspects and case study

The system development can be tested by engineering students since trainers can make use of the knowledge management of this laser transformation hardening simulator to assist technical courses. The system can be employed as a supported tool not only in distance courses but also in traditional and semi-presential ones. The students can take advantage of the virtual laboratory to determine the right values for the transformation hardening process and to see the general procedure including tests and analysis aspects. Students can get confidence and competence in basic laser process techniques, which will be required later in their professional tasks. The web-based simulator, as a support to the traditional instructional methods, reduces the time and cost training and provides time-space flexibility in the teaching-learning methodology.

During the 2009–10 course the educational staff of the Physics Department at the ETSII-UPM have taken advantage of the virtual laboratory as a learning activity for the students of a university degree course. The course *9012—Introduction to Fundamentals and Applications of Lasers* (*Introducción a los Fundamentos y Aplicaciones del Láser*) is located in the first semester, begins at the end of September and lasts until the end of January, 3 credits (30 hours of traditional lectures) and has one lecturer and 27 enrolled students. The syllabus course includes the following chapters: Laser fundamentals, lasers, Types of lasers, Optical applications of lasers, Chemical and environmental applications of lasers, Industrial applications of High Power Lasers, Lasers applications in micro/nanotechnologies, Energetic applications of the high-intensity lasers and Advanced applications. The course teaching style was fairly traditional with lectures and laboratory works. The virtual laboratory is introduced as an interactive learning system helping students to learn the basic laser transformation hardening procedure. In this way the course lecturer can configure an virtual practice for his group of students. The objective of the homework is to determine the sets of right parameters values of a steel laser transformation hardening process using the virtual laboratory. The

Table 2. Summary of the assessment of the simulator

	Question	Students	Answers	1	2	3	4	5	Ave.
1	It is very easy to use	17	17	1	0	1	1	14	4.59
2	It is very useful to learn	17	17	1	0	2	7	7	4.12

student can connect the web server from home or the campus computer facilities and interrupt and postpone the end of the exercise at any time. When finishing the exercise, the students record the results and write a final report including these data. Finally they send it to the lecturer to be evalu.

5. Assessment of the simulator

To check the effectiveness of the simulator, at the end of the academic period, students completed a questionnaire by the ETSII-UPM elearning system called AulaWeb [19–29], providing anonymous and very interesting information and feedback. First of all, they were asked to answer a set of questions. The responses were given a five-position scale graded from 1 (Strongly disagree) to 5 (Strongly agree). Results of the 17 answered questionnaires shown in Table 2.

The results of the questionnaire for the students were conclusive: the use of the simulator was very positive in the case study. Moreover, on this questionnaire students also had the chance to put forward written comments in order to explain or develop their scored responses. The written comments are closely correlated with previous responses.

'Instant feedback', 'clear and interesting explanations', 'multimedia results', 'flexibility', 'good tutorial', 'a true didactic tool' and 'ease to use' were seen as some of the major benefits. Drawbacks: students wished to 'select a bigger set of parameters values', 'process different kinds of materials' or 'perform other laser applications'.

Anyway, overall comments were positive, so much so that the majority would be pleased if similar systems were used in other courses.

6. Conclusions

A web-based virtual laboratory of laser transformation hardening including an expert system has been developed. Users only need a web browser to take advantage of all the functionalities of the system. The application database has a enough number of experiments to show how the values of the main parameters affect the process results, so the user can carry out a prediction-evaluation after the real process experimentation.

The use of this virtual laboratory is viewed positively by students and tutors. The system is not only very easy to manage but also gives very useful feedback to students and facilitates the laboratory practices with large groups of students.

This kind of web-based simulators may help to organize flexible activities and to reduce distance barriers not only for local or national students but also for other students from international institutions and provide the access to vocational and lifelong learning and training for laser technical staff. Moreover it can avoid dangerous situations in real life.

For all these reasons it is worth developing a system like this for, at least, one year, including application design, software implementation, content development and validation phases.

In the future the virtual laboratory can be extended to other process parameters (sample geometry, laser type . . .), to other laser applications (cutting, welding, coating . . .) and to other materials (metallic and non metallic ones) and take in account the possibility of the online control of the system.

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Ángel García-Beltrán is an Assistant Professor in the Dpt. of Control, Electronics and Computer Science of the Universidad Politécnica de Madrid. He investigates in Laser Industrial Applications, teaches several programming courses and is also active in innovative engineering education methods using the web.

José-Luis Ocaña is the Director of the Laser Center UPM and member of several scientific committees in the field of laser technology and applications. From 2005, member of the Executive Board of the European Laser Institute. From 2006, Chairman of EULASNET II (Eureka Umbrella for Laser Technology and Applications). He has actively promoted and participated in national and European R&D initiatives in the field of scientific and industrial applications of high power lasers, especially in the sub-fields of laser surface treatments, laser micromachining and on-line monitoring and control of industrial laser applications.

Carlos Molpeceres is Technical Director of the Laser Center UPM and Head of the Group for PV applications. His current research activities include laser processing of materials at micro and nanoscale for energy and biological applications. He combines these activities with his teaching position as Professor at UPM.

Miguel Morales is an Assistant Professor in the Applied Physics Department of the Universidad Politécnica de Madrid. He investigates in Laser Industrial Applications and teaches several Physics courses.

José Manuel González is researcher at Laser Center UPM.

Manuel Blasco is researcher at Laser Center UPM and an specialist in advance laser welding manufacturing processes.

Danut Iordachescu is researcher at Laser Center UPM and professor within the Applied Physics Department (ETSII-UPM). During 30 years of academic and research career, he has contributed more than 150 articles in the fields of welding and industrial engineering, and has participated in the development of innovative teaching tools and methods through various European projects.