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Technological and scientific landscape of laser cladding process in 2007

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ABSTRACT

In the last 30 years, public and private organizations involvement in laser cladding R&D activities is increasing. These activities are mainly conducted in universities, public research institutes and technical centres of private companies worldwide. This study shows a bibliometric analysis of the patents and scientific publications in the laser cladding field for the period ranging from 1985 to 2007. This seeks to identify the activity and trends in its environment for strategic purposes. All the laser cladding processes and all the substrates (steel, aluminium and superalloys) used for coating, repairing and 3D fabrication were taken into account. At first, the world patent production was analysed in terms of volume (580 patent families found since 1985), frequency and applications. Then, the same strategy was applied to the scientific publications for a total volume of 588 targeted papers. Using bibliometric techniques, an analysis and mapping of the information was performed to highlight the temporal, geographical and institutional aspects of R&D activities. The patented applications were also classified in order to identify opportunities. This study shows the evolution of the scientific and technological environments of the laser cladding technology and can help public or private organizations to generate new ideas, gain awareness of emerging trends and validate the relevance of projects.

1. Introduction

Laser cladding consists of covering a substrate surface with a coating of a different nature. This process can be carried out in different ways: precoating, wire feeding, lateral [1] or coaxial [2] powder injection. In powder injection, the most used way, the cladding powder is injected into the laser beam by an inert gas flow, as shown in Fig. 1. The energy delivered by the laser is absorbed both by the powder stream and the substrate material. This enables the melting of the in-flight particles and the substrate surface in the same time. A clad is formed by moving the sample under the laser beam (Fig. 1). The partial overlapping of each individual clad provides a homogeneous coating. A slight dilution of the cladding material into the substrate generates a perfect metallurgical bonding. Over the last 30 years, many studies on laser cladding have been carried out. The objectives of these studies were, on the one hand, to develop the process itself (use of CO_2, Nd:YAG or HPDL lasers, powder injection nozzle, powder feeder, etc.) and its applications (coating, repairing and 3D free forming). On the other hand, part of the R&D effort focused on improving the mechanical properties (hardness, elastic modulus, wear resistance, corrosion resistance) of laser cladding-treated substrates: steel, aluminium, nickel-base superalloys, magnesium, etc. For this purpose, many authors have investigated the formation of high mechanical property coatings by intermetallic precipitation [3–8] or metal matrix composites fabrication [9,10].

While the laser cladding technology has been around for more than 30 years, the reduced costs of laser sources, the increasing potential for processing materials, the emergence of rapid prototyping and other manufacturing applications have made it an appealing technology to consider for many applications. With recent projects initiated by the National Research Council of Canada, there was a need to gain a deeper understanding of the environment in which the laser cladding technology was involving, as well as to assess the opportunities for new applications and the development of the technology. The scope covered by patented applications, the identification of major and emergent players and their specific R&D activity proved to be of particular interest. Also required was an overview of the research activities performed in organizations around the world and a way to evaluate the impact of the research they performed.

The evolution of scientific and technical fields can be monitored by analysing the flow of codified knowledge or footprints of the scholarly communication process and patenting activity in science and technology (S&T). The mathematical and statistical methods applied to either print or electronic publications with this objective are generally referred to as bibliometrics [11]. In this study, basic bibliometric indicators are used to assess the laser cladding field, such as publication and citation counts, cross-analysis of patent assignee or patent classifications and publication date fields, to name

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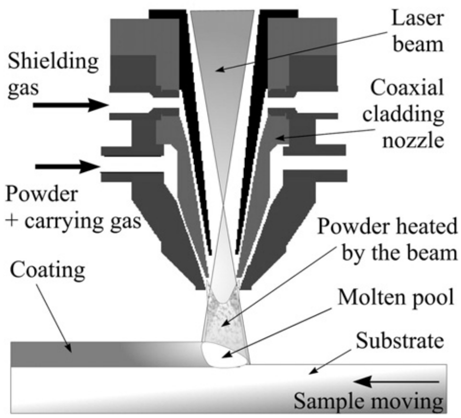

Fig. 1. Principle of laser cladding with coaxial powder injection.

just a few. These indicators enable monitoring of the activity and trends in the laser cladding field and will help outlining a representation of its S&T landscape.

Hence, the objective of this study is to generate a representation of the S&T environment in which evolves the laser cladding technology. This first approach is intended to use patent information and scientific publications, to capture these signals and to transform them so they could be useful for a more in-depth analysis process implying domain experts. More specifically, the level of activity and identification of the players involved in R&D efforts, their relative impact and actual implication in these efforts have been analysed. Also, an effort has been done to know what types of applications were protected by patents and to find opportunities for development of new applications.

For this purpose, two different datasets were created, each of them covering a 22 years period, from of 1985 to 2007. They provided a different perspective on the development of laser cladding research and technology. They are:

(i) A patent dataset: Patents being protected technical disclosures, analyzing patent data is generally recognized as an effective means of characterizing the technological evolution of a knowledge domain, even considering the limits of patent information [12]. This dataset served to characterize the technological activity, to identify the players (patent assignees) and to categorize the diversity of patented applications.
(ii) A scientific publications dataset: This dataset was used to identify the level and impact of research activity in organizations, mostly universities and government laboratories. A geographical mapping of results was created.

2. Methodology

2.1. Technological activities (patents)

The databases used to build the initial patent dataset were USPTO's US Granted (US) and US Applications (US-A), the European Patent Office (EP), Patent Cooperation Treaty (PCT-WO) and the Japan Patent Office (JP) through Wisdomain Inc's FOCUST product. After extracting data from this service, the dataset was completed by searching a patent database with a more international coverage: PlusPat database on Questel-Orbit was used to retrieve patent data previously non existent in the original dataset, and retrieved patent data mainly from regional patent offices (France and Germany). Patent family information in this study came from the INPADOC database.

The search strategy used for information retrieval came from an iterative process that can be summarized in two main steps. The first one expanded the simple usage of the term "laser cladding" for retrieval by adding "laser welding" in conjunction with relevant terms, such as repair, deposition or coating (see Eq. 1). After observation of the results, the International Patent Classification (IPC) classes H01 and H05 were used to restrain noise coming from electrical oriented applications (semi-conductors, printed circuits), which were not the goal of this study. The IPC is a hierarchical system used by more than 100 States to classify and to retrieve patents documents and this can be used, among other usages, to add precision to a search strategy. Other usages of IPC classes in the search strategy were unproductive in that particular case.

2.1.1. Equation 1: Boolean search equation

((laser or energy beam?)(s)(clad* OR surfacing OR
× (welding AND ((substrate? OR metal* OR powder?) AND
× (repair* OR deposit* OR coating?)))))NOT IC = (H01* or H05*) (1)

There was still some noise in the results from Eq. (1) coming from irrelevant types of applications. In order to add precision to the search strategy, more stop-words were added in the query, such as thin-film, ablation, resin, semiconductor, quantum-well, GaAs or circuit (see Eq. 2).

2.1.2. Equation 2: Boolean search equation without irrelevant types of applications

((laser or energy beam?)(s)(clad* OR surfacing OR (welding AND ((substrate? OR metal* (2)
× OR powder?) AND (repair* OR deposit* OR coating?))))) NOT ((IC = (H01* or H05*)) OR (thin−film*
× OR target sintering OR ablation OR Resin OR resins OR vacuum optical OR semiconductor*
× OR semi()conductor* OR quantum−well* OR ((quantum or multiquantum)(s)well) OR GaAs OR InGaAsN
÷ GaAs OR circuit OR Circuits OR (Fibre? OR Fiber?))

Manual screening of the results was performed to eliminate remaining irrelevant patent records. Finally, all records from this dataset were extracted and transferred to an analysis module for duplicates removal and further processing. Cleaning of data was done to normalize inventor and assignee names, without paying attention at this point as to who was the actual owner or licensee of the patent. For each invention, only one document represents a whole patent family, according to the INPADOC definition of a patent family: "All the documents directly or indirectly linked via a priority document belong to one patent family."[13]. By counting patent families instead of individual patents, an effort is made to reduce occurrences of the same invention to one single occurrence, instead of taking into account each national patents protecting the same invention in different countries. After all this cleaning and processing, the final dataset of patents contains 580 patents records.

2.2. Scientific activities (scientific publications)

In order to monitor scientific activities, Eq. (2) has been adapted as a query to use in ISI's *Web of Science®* database. ISI *Web of Science®* is a multidisciplinary database indexing S&T publications from 1945. Even if this database does not specialize in engineering information, its main advantage to date is the indexation of citation information. Availability of citation information enables the evaluation of research impacts, analysis of the structure of knowledge domains and understanding of knowledge networks within and between scientific fields [14]. This strategy has lead to 588 scientific publication records, although a higher number of publications (2115 records) can be retrieved in giving the same search strategy via a multi-database search in specialized databases (*Inspec*, *Ei Compendex*, *Metadex*, *Weldasearch*, *Aluminum Industry Abstracts*). This higher number of publications is generally caused by the retrieval of different types of publications (including proceedings) that are in a wider range of languages (Russian, Chinese, etc.). For example, when limiting results to English language publications only and using the same query in this multi-database search listed above, numbers drop fast (from 2115 to 996 records). ISI's *Web of Science®* coverage is mostly core international journals that are peer-reviewed and only indexes publications providing English titles, abstracts and keywords. Moreover, the comparison of resulting datasets from these two strategies demonstrated that the ranking of the different institutions was not highly affected when considering only journal articles in the English language. Therefore, the advantage of having access to citation information prevailed on the loss of some bits of information, as the depth of search was not the goal at this point of the analysis.

From the 588 unique records retrieved from ISI's *Web of Science®*, the author's affiliations were extracted with regards to the number of citations received by these institutions, sorted by the publication year of the cited paper. This basic indicator is informative to quantify the relative impact of the research output, i.e. use and transfer of the knowledge produced. Although the indexing scheme of this database was fairly good when it comes to information on the author's affiliation, there was still a need for some data cleaning. Unification of author affiliation has been done to the best of our ability, as it was sometimes unclear or incomplete. Also note that self-citations were here considered as a normal behaviour in the scholarly communication process and have not been discarded [15]. This time-related citation information was then visualized and displayed on a geographical representation of the world's countries on which the research centres (Universities, Government agencies or Industry) were also identified. For practical reasons, the number of citations received was grouped by periods, so it would be easier to display this information on a map.

3. Results

3.1. Technological activities (patents)

A first indicator of the laser cladding technological activity is the number of patents according to their application year. As shown in Fig. 2, the number of patents increased from 9 to 28 between 1984 and 1985. If we take into account the delay in development of the actual patent application, it assumes that the laser cladding activities started at the beginning of the 1980s. This date corresponds with the emergence of the first high-power CO_2 lasers, i.e. higher than 1 kW. From that period onwards, a linear growth of the laser cladding activities since 1985 can be seen in Fig. 2. The highest number of patents per year related to laser cladding was 43 in 1997 and 42 in 2001.

For reference only (no figure), it showed that Toyota and Nissan have the highest number of patents, 51 and 49, respectively. These patents mainly protect applications related to the laser cladding of valve seats, pistons and cylinders for automotive engines. The R&D effort of these companies, as shown by their patenting activity, was mainly performed between 1985 and 1992 for Toyota, and 1993 and 2001 for Nissan.

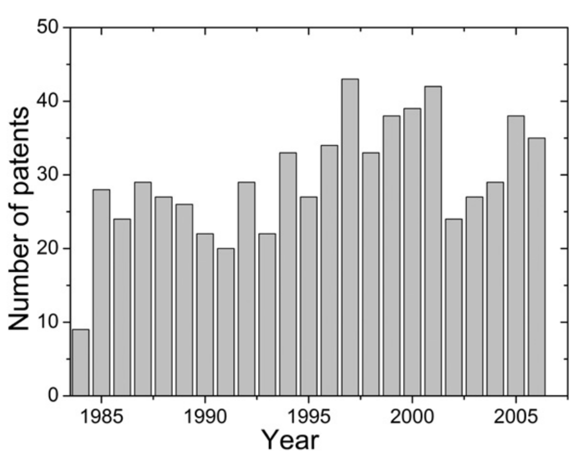

Fig. 2. Number of patents by application year.

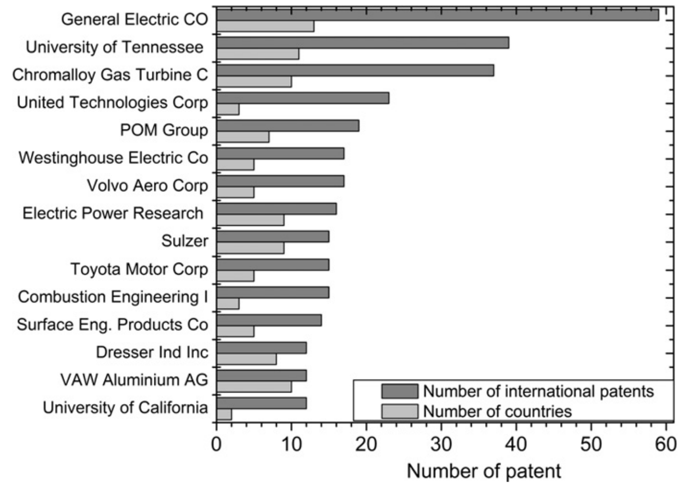

Fig. 3. Number of patents in more than 2 countries and total number of countries covered by these patents, per company (15 first companies).

General Electric Co. ranks 3rd for applications mainly related to the rebuilding of turbine blades (aeronautic or electric), with 36 patents from 1989 to 2001. Then come Ishikawajima Harima Heavy Ind. Co. and Mitsubishi (Heavy Elec. Motor Ind.), with numerous patents related to internal/external coatings for tubes, from 1987 to 1996. As for the other companies, the scattering of patent numbers *vs.* application years has been homogeneous in the last 20 years. No particular activity peak was revealed as shown in Fig. 2 by a steady linear growth, despite the emergence of new high-power lasers (Nd:YAG laser, HPDL or Nd:fiber laser). Nonetheless, some news assignees such as Rolls Royce, POM Group, University of Tennessee Research and Daimler-Chrysler, absent from the landscape before 2000, seem to have entered the field and started patenting in recent years.

Counting the absolute number of patents in a dataset can be misleading. Even though the rules for the submission and examination of patents tend to be more consistent around the world, some national systems make the publication of patents easier than others for many reasons [16]. This artificially increases the ranking of assignees for some countries. In order to avoid this artificial inflation, assignees were ranked by counting only international patent families, i.e. patent families which contain patents deposited in at least 2 different countries, as shown in Fig. 3. The use of patent family information therefore introduces a certain value to patents if the financial resources required to apply for a patent in different countries, but also to maintain were taken into account. This highlights the company's protectionism and its strategic interest for the invention. As shown in Fig. 3, General Electric Corporation ranks first with 59 patents deposited in more than 2 countries regarding turbine blades rebuilding and peripherals of the laser cladding process (powder feeder, preheating system, etc.). Due to this classification, the University of Tennessee ranks second with patents related to automotive components (cylinder bores, pistons, etc.). Moreover, assignee protection is found in a higher number of countries for new players in the field (less than 7 years), such as POM, Rolls Royce or the University of Tennessee. It is also interesting to underline that some universities in the dataset are very active in world protection of their laser cladding patents (University of Tennessee and University of California). It could prove valuable to investigate why these Universities are pursuing this strategy, which is more generally adopted by private companies.

Having obtained information on the players involved and an overview of the level of patenting activity, the next step was to investigate which specific applications of the technology were

Table 1
Assignees per fields and applications

Categories	Applications	Assignees
Automotive	Piston, cylinder, valve seat	Nissan, Toyota, Sulzer, Fuji Valve, Daimler-Chrysler, Hyundai, Univ. of Tennessee Research
Turbines	Load-bearing components, casings, inner face/inside, tubes, pipes	General Electric, Westinghouse electric, Ishikawajima Heavy, Nippon Steel, Rolls Royce, Alstom
Weapons et al.	Fuel-rocket engine wall	United Technologies, Volvo Aero, Rheinmetall,
Instruments/manufacturing process	Flow regulator/powder control	Nissan, Toyota, General Electric, Mitsubishi, Univ. of California, National Research Council Canada
	Laser machine; head, support, nozzle	Nissan, Toyota, General Electric, Ishikawajima Harima Heavy, Rolls Royce, Univ. of Tennessee Research, Sulzer, POM, Univ. of California
	Quality insurance	Nissan, Toyota, General Electric
Prototyping 3D	Direct metal deposition 3D	Toyota, Westinghouse, Sulzer
	3D shape laser consolidation	National Research Council Canada, HR Tech., Sandia, Solidica
Others	Nuclear reactor element	General Electric, Ishikawajima Harima Heavy, Westinghouse, Toshiba, Electric Power Res. Inst., Sumitomo, Japan Atom Res. Inst.
	Miscellaneous	Nissan, Toyota, General Electric, Mitsubishi, Ishikawajima Harima Heavy, Nippon Steel, United Technologies, Univ. of Tennessee, Technogenia, Batelle, Praxair…

developed and protected. Generally speaking, analysis of the IPC classifications could be used to categorize and generate informative insights on the different applications described and protected by these patents. For this study, that approach has proven to be unproductive and unfruitful. Instead, a semi-manual textual analysis of the patents was performed. Based on this, the applications that were identified have been categorized in 5 main groups. All patents related to the process itself (with no specific applications) were not considered and therefore left aside.

Table 1 shows the patent assignees' relation with categories and applications. The main categories identified are automotive, turbines (electric or aeronautic), weapons, instruments/manufacturing related to the laser cladding process itself (powder injection nozzle, powder feeder, etc.), 3D freeform fabrication/prototyping and finally, others (such as nuclear reactor components). The sub-category "miscellaneous" was included in this last category (Others). It contains applications of laser cladding that do not fit the main categories cited above. Nevertheless, most of these miscellaneous applications (knifes, forging tools, cutting tools, drill bit, bushing, orthopaedic implants, etc.) are of particular interest precisely because they are recent explorations in non traditional areas.

Different conclusions can be drawn from this analysis. Clearly, there is an evolution in the types of laser cladding applications. Once concentrated on turbine blades, automotive, processes and weapons in the 1980–90s, the types of application are now broader (knifes, forging tools, cutting tools, drill bit, bushing, orthopaedic implants, etc.). The same can be said for automotive applications (casting components, bumpers), which are now broader than the classic ones (piston, cylinder, valve seat). The development of applications is now characterized by: the laser cladding of smaller and more specific pieces, the use of insulating (nuclear reactors) and decorative (bumpers) coatings, and the intense growth of 3D freeform fabrication.

3.2. Scientific activities (scientific publications)

The second dataset, which contains scientific publications of journals, provides the basic elements needed to identify the research institutions around the world and the relative impact of the work initiated by these organizations. Fig. 4 shows the annual number of papers in the scientific publication dataset. It outlines the exponential growth of publication activity in the laser cladding field starting in the mid-1980s. Among factors that could explain this development, there is the general implementation of high-power lasers around the world and the increasing needs from the industrial sector for high wear resistant coating applications. Moreover, as discussed later, a growing part of this rise comes from researchers affiliated with China's research organizations, either as unique institutions or in collaboration with other countries.

Raw citation counts for each institution counting more than 2 citations i.e., the number of times papers attributed to an institution have been cited at least two times, was extracted from the dataset. The publication years of the cited papers were also extracted in order to determine during which periods the research was performed. Although some relative impact indexes could have been used (number of citations as a function of number of publications), it was decided not to do so. Relative impact indexes, known as impact factors, are widely discussed and usually effective in assessment exercises [16]. In fact, among parameters that could affect the number of citations received, time and output strength are crucial but the effect of the growth of publications has been voluntary kept in the signal. Finally, a geographical mapping of the results was created, for each of the three main world regions identified, namely Asia, Europe and North America (Figs. 5, 6 and 7).

The most obvious observation from these maps is that the research impact between these regions is unevenly distributed with regards to time. In North America (Fig. 7), the highest impact can be attributed to papers published by the Department of Mechanical and Industrial Engineering of the University of Illinois at Urbana-Champaign during the 1986 to 1994 period. In comparison, much of the attention received by papers in Asia (Fig. 4) is concentrated in the last ten years. As underlined earlier, it also correlates with a rising output of publications in China during the same period. Europe's position tends to be somewhere between the two other regions' with many institutions showing a higher impact between 1990 and 1994, and others receiving more citations between 1995 and 2003. Another general observation is the type of institutions with which researchers are affiliated. In North America and Asia, research is performed in

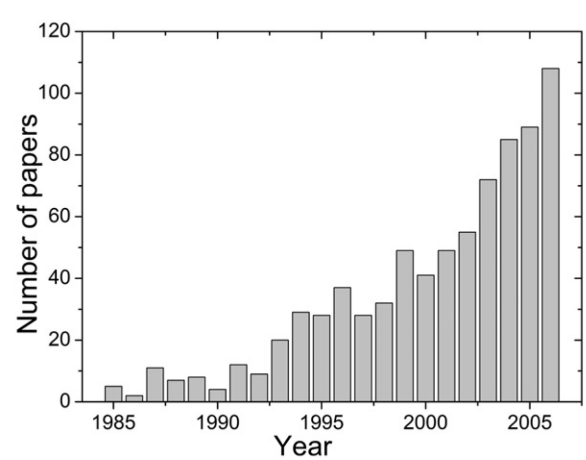

Fig. 4. Number of papers per application years.

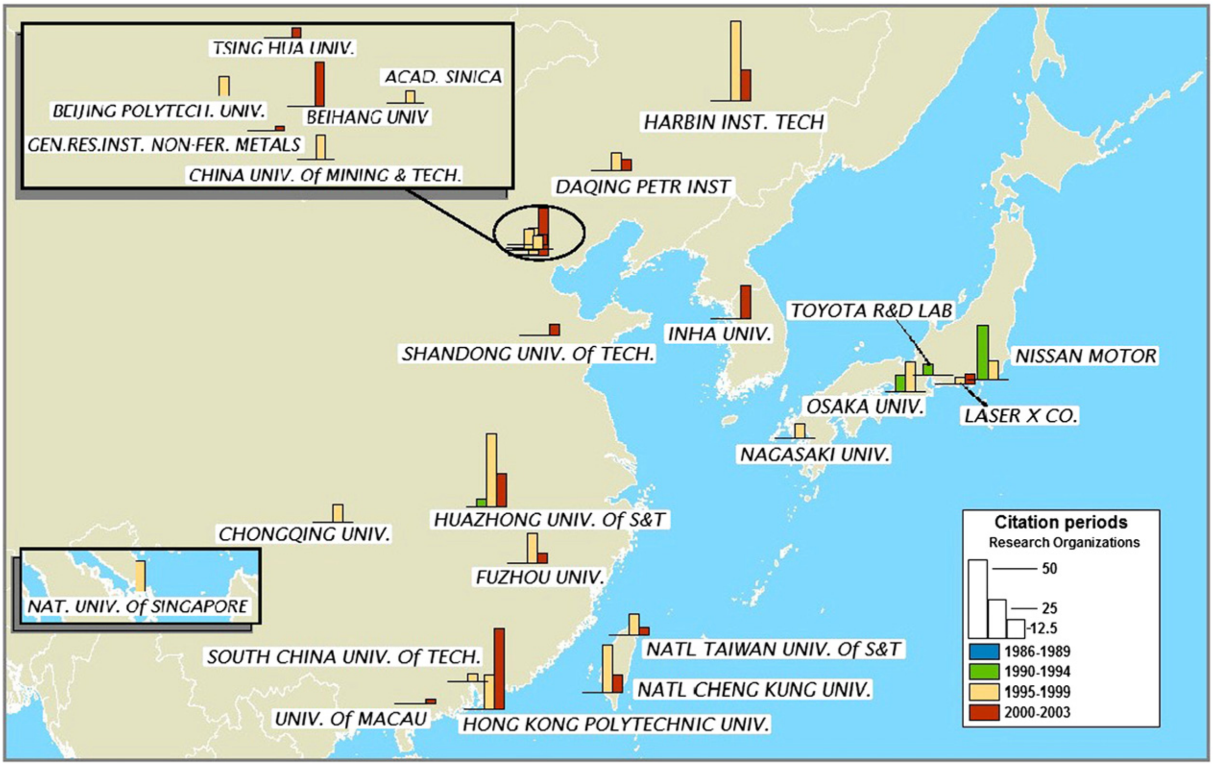

Fig. 5. Number of citations received by papers from researchers affiliated with institutions located in Asia.

Universities (with the notable exception of Japan, where three organizations are companies), whereas in Europe, four of them are government laboratories.

In order to capture recent trends in laser cladding research by these institutions, the title, abstract and keywords of recent papers from cited institutions during the period of 2000 to 2007

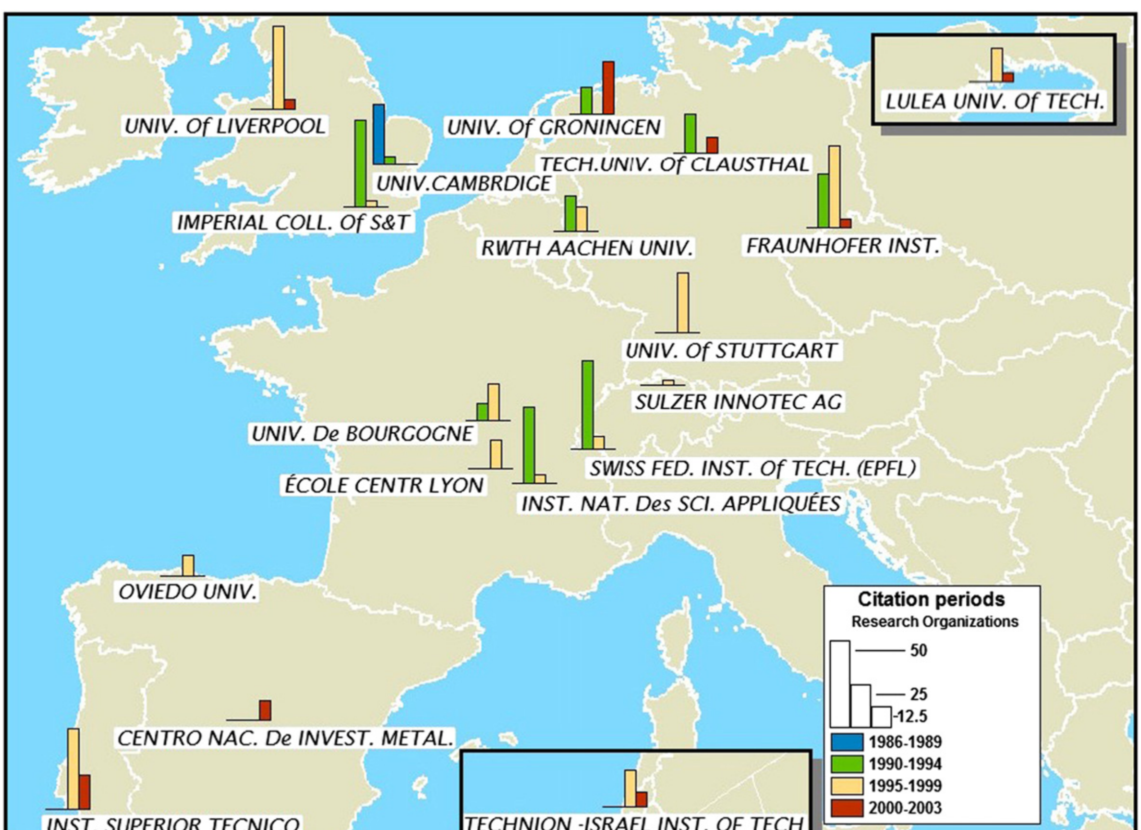

Fig. 6. Number of citations received by papers from researchers affiliated with institutions located in Europe.

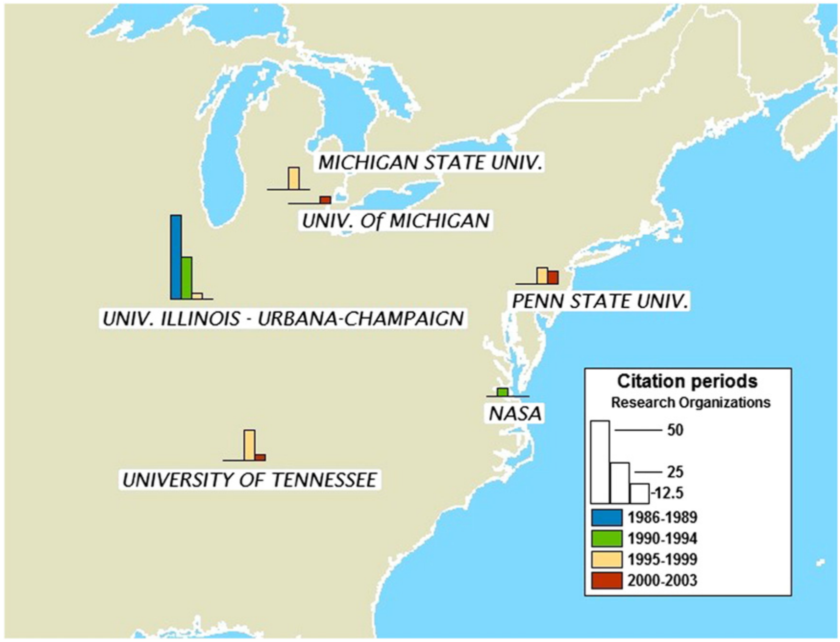

Fig. 7. Number of citations received by papers from researchers affiliated with institutions located in North America.

have been analysed. Indeed, the small size of the dataset analyzed made that possible; a larger dataset would require the use of statistical analysis of textual elements (keywords, etc.). For each region, interesting trends in research areas have been identified. They are:

Asia:
- (i) Development of transition metal silicides-based (Ti_5Si_3, Mo_2Ni_3Si, NiSi) or intermetallic alloys (NiTi, NiAl, TiCo) for wear applications, done at Beihang University and The Hong Kong Polytechnic University, China [17–20].
- (ii) Development of Metal Matrix Composites (MMC) based coatings with Al_2O_3, SiC, WC, TiC reinforcements. These coatings are applied on Al-based substrates at Hong Kong Polytechnic University, on magnesium alloys at Jilin University and on Steel and Ti-based substrates at Harbin University, China and Laser X Co, Japan [21,22].
- (iii) 3D free forming at Laser Institute, Hunan, and Shenyang Institute of Automation, China [23–25].

Europe:
- (i) Fundamental research leading to the understanding of the laser cladding process, for example at the Instituto Superior Tecnico, Portugal and University of Liverpool, UK [26,27].
- (ii) Development of MMC wear resistant coatings at the Instituto Superior Tecnico, Portugal, Technical University of Clausthal, Germany, University of Groningen, Nederlands and Fraunhofer IWS, Germany [28,29].
- (iii) Free form manufacturing of functionally graded 3D objects at Université de Bourgogne, Le Creusot, France and The University of Manchester, U.K. [30–32].
- (iv) Cladding of light components, such as aluminium part at the University of Groningen, Nederland and Fraunhofer IWS, Germany, or magnesium parts at Université de Bourgogne, Le Creusot, France [33].
- (v) Rebuilding of components and tools at the University of Liverpool, U.K., Fraunhofer IWS, Germany, the Centro Nacional de Investigaciones Metalúrgicas, CENIM, Spain or University of Ljubljana, Ljubljana, Slovenia [34].
- (vi) Cladding with foam coatings at the University of Groningen, Nederland [35].
- (vii) Elaboration of biomaterial calcium phosphate coatings by laser cladding at Universidad de Vigo, Spain [36,37].

North America:
- (i) Cladding of wear resistant steel tools, i.e., manufacturing cutting and stamping dies at the University of Michigan, USA [38].
- (ii) 3D free forming at Ohio State University and Iowa State University, USA [39,40].
- (iii) Use of TiB_2 coatings for wear and sliding applications, and cladding of copper on alumina at the University of Tennessee, USA [41].

There are clearly a lot of recent activities in the development of wear resistant coatings, demonstrated by the fact that 11 of the most active research centres are working in this specific research area. Most wear resistant coatings tested are MMC coatings with reinforcement of SiC, WC, TiC and matrix of Ni, Al and Fe, applied on steel, aluminium or brass substrates. Other applications with high potential are the 3D freeform manufacturing, the non equilibrium synthesis of advanced materials (TiB_2, Ti_5Si_3, $NiTi_2$), the use of foams (Al-based) for coatings or components and, finally, the rebuilding of components and tools.

4. Conclusion

This study shows that:

- (i) Although there are a rising number of scientific publications in the laser cladding field, an equivalent growth in the number of patents has not been found. Factors that limit incentives to protect dedicated applications of the laser cladding process may be investigated. However, new players (assignees) are protecting their invention more widely, in a higher number of countries.
- (ii) In terms of applications being patented, the laser cladding of smaller and more specific pieces, the use of coatings for insulating (nuclear reactors) and decorative (bumpers) purposes and the intense growth of 3D freeform manufacturing are clearly developing.
- (iii) There is a notable growth of the research activity in Asia, particularly in China, as revealed by the data in our dataset. Europe is also active, with specific research on aluminium components.

(iv) Some research trends are moving to interesting areas such as 3D freeform manufacturing, non equilibrium synthesis of advanced materials and the use of foams as coatings.

The use of basic bibliometric techniques has proven to be an informative way to outline the scientific and technical landscape of the laser cladding field. Findings were instrumental to add significant insights to decision-making processes such as strategic planning of R&D activities, and to identify opportunities for the development of new laser cladding applications. This type of information is useful when combined with opinions from experts and other types of information such as market reports, industry news, etc. The use of additional data from multi-databases that would include conference proceedings will be done at a later stage of the project to give a different view of the laser cladding S&T landscape. Building on this study, a deeper analysis of collaboration patterns between institutions and identification of research group networks will also be part of future research.

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