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The Process of Scientometrics in the Field of Thermal Barrier Coatings as an Indicator of the Progress of Materials Engineering

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ABSTRACT

Thermal Barrier Coatings (TBCs) reduce the working temperature of the substrates and protect them from hot corrosion and oxidation. In recent years, scientific research into the TBCs and their innovative applications have gained increasing popularity insofar as since 1980, the number of relevant published articles has increased up to about 400 times annually. These coatings play an essential role in enhacing the efficiency of the substrate and engines and for this reason, tracking their research process can help advance future research studies and accelerate their progress expansion rate. According to the results from scientometrics and tracking research, the United States was initially ranked first in article production in this field of surface engineering, followed by Germany and England. However, since 2011, China has remained in the first place by a large margin. The combined annual growth rates of Iran and India reached their highest value, indicating that these countries concentrated on the gas turbine and energy sectors. Since these coatings play a significant role in improving the performance of gas turbines, variations in their scientific progress can be considered one of the leading indicators of material engineering progress in such turbines.

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1. INTRODUCTION

Thermal barrier coatings (TBCs) are refractory ceramic materials that protect the metal substrate from heat or even direct flame impact like an insulator [1-4]. These coatings are commonly used at temperatures higher than 1200 °C that can reduce the working temperature of the substrate up to 300 °C. Of note, these coatings are mainly used in air and ground gas turbines [1-8]. In terms of the coating method, these coatings can be formed by different methods such as double glazing, thermal spraying, use of vapor phase, and anodizing on the substrate [9-10]. TBCs can have different chemical compositions such as alumina, mullite, and magnesia-based composites. Generally, TBCs are zirconium materials that are stabilized with different stabilizers to

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prevent the transformation of tetragonal martensitic to cubic ZrO_2 during operation, which is caused by volume change and subsequent cracking [11,12]. The most famous of these stabilizers is Y_2O_3 [12]. An interface layer is used to improve the adhesion strength of these coatings to the substrate. This interface layer is usually MCrAlY in which M can be replaced with Fe, Co, Ni or their combination [13,14]. Another type of middle layer is aluminizing that can be reinforced by Au or Pt [15]. Another generation of these coatings is Environmental Barrier Coatings (EBCs) that work at lower temperatures as the protection against vapor and other environmental threats such as low-temperature oxidation [16,17].

The high importance of thermal barrier systems in the industry has become the incetive to carry out more research studies every year to improve these systems to the point where materials such as High Entropy Alloys and max phases have been introduced as an interface layer, and pseudo Crystals have also been considered as a new thermal barrier system or as a reinforcement of new systems [18-20]. These are just some of the developments made in surface engineering materials. Significant evolutions have also been reported in the field of Air Plasma Spray (APS) and High-Velocity Oxygen Fuel (HVOF) processes and their sub-branches [21-24]. These developments are made available annually through scientific documents such as articles or patents. Accumulation of the scientific records and documents shows the increasing attention of the academicians and industrial experts as well as the development units to these coatings. Monitoring the status of these documents to find a dynamic and constructive way to progress in TBCs is a rational solution known as scientometrics.

Scientometrics can be considered as both quantitative and qualitative analysis of the production process, distribution and use of scientific information, and factors affecting it. In addition, this science describes, explains, and predicts this process for different purposes of planning, policy-making, advancement, and Scientific-research awareness and foresight are used in individual, group, organizational, and international dimensions [25]. Scientometry is one of the most common methods for evaluating scientific activities, considering the number of scientific articles as one of the criteria for production comparison and presentation of science in different countries [25,26]. The objective scientometry pursues is to reveal the characteristics of science and scientific research by examining these variables separately or in a suitable combination. One of the most important objectives of scientometrics is to establish descriptive indicators systems in different scientific communities. The continuous and regular publication and review of such indicators can be a valuable and efficient element for research management and policy-making policies as well as allocation of budgets and facilities in science to make them more practical to meet the regional requirements [25-27]. The analysis results help determine the flow structure of the scientific documents and their citation processes. Quantitative evaluation of sciences leads to development while assisting the officials and planners in making the most of financial and human resources at lower costs and being effective in optimizing the economic-social structure of a country. In addition to looking for the quantitative aspects of science and research, scientometry also measures and determines the standards of various managerial and organizational aspects of science. On a broader level, scientometrics can be considered one of the influential factors in the continuous circulation of research activities in any scientific field, which directly deals with the quantitative evaluation of science [27,28].

This report analyzes research papers written about TBC from 1980 to the end of 2021 using Scopus data. In this regard, the findings were analyzed to monitor the progress of TBCs and identify the leading countries in this field. In addition, the country which has made significant strides in this field was identified, thus making it possible to predict the trend of future changes and determine the policy of research in this field.

2. MATERIALS AND METHODS

Articles on TBC written from 1980 to 2021 in Scopus with the keywords "(TITLE-ABS-KEY ("thermal barrier" OR "thermal barriers") AND TITLE-ABS-KEY (coating OR coated OR coatings OR coat)) OR TITLE-ABS-KEY (thermal AND TBC))" were searched and found. A total number of 11253 articles were published, and the information of the articles such as their authors, publication year, title, reference title, abstract, organizations and affiliation, keywords, and other related data were prepared as a Commonly Separated Value (CSV) file. Next, the obtained data were processed and analyzed using VOSviewer software. The extracted graphs were analyzed using a detailed study of relevant sources and articles in the field of TBC.

3. RESULTS AND DISCUSSION

Figure 1 shows the results obtained from the number of publications published in different years (the mentioned period). According to this figure, this topic has clearly gained in increasing significance every year, as evident from the increasing trend in the number of articles as time went by.

Since 1997, more attention has been paid to this type of coating due to the greater demands for energy and transportation. The increasing trend has been maintained in all years until 2017 and 2018, when around 700 valid scientific documents were published annually. This shows the importance of these coatings in various industries such as gas turbines, power plants,

petrochemical industries, aerospace, military, defense, and transportation. On the contrary, considerable attention to surface engineering sciences in recent years shows the need for the temperature rise in many industries since an increase in temperature leads to the higher efficiency of the internal combustion engines [29]. Therefore, more research in this field is required to improve productivity in industries.

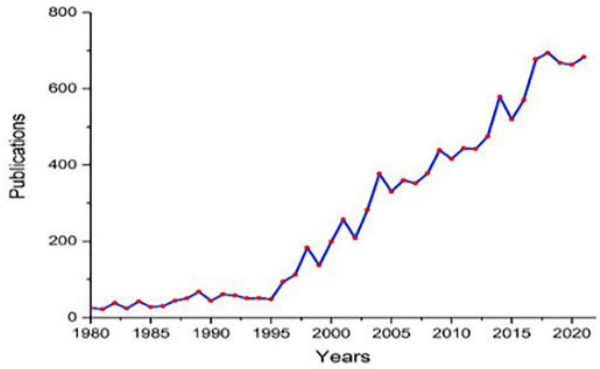
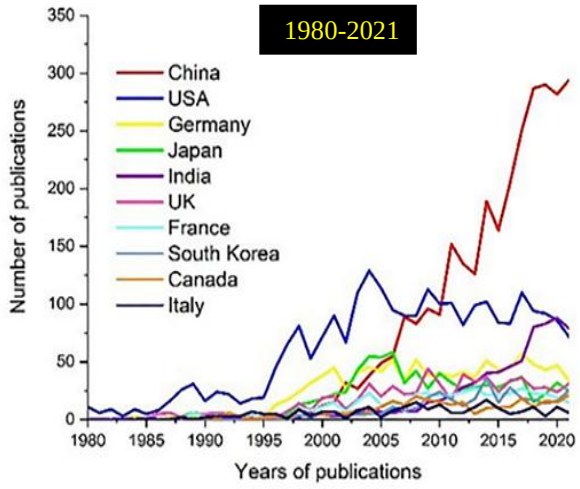


Figure 1. The number of articles published about TBC in different years

Figure 2 shows the number of published articles in 10 leading countries in the field of TBCs. Followed by separating the articles produced according to country, it can be concluded China with about 3000 publications is the leader in this field. Other countries such as the United States, Germany, Japan, and India are in the next positions, showing that these countries are either active in producing the raw materials of these coatings or are developing the technology for applying these coatings, both of which indicate the attention of these countries to the TBCs and their development. However, due to the importance of industries in their country, these countries pay special attention to the mentioned coatings.



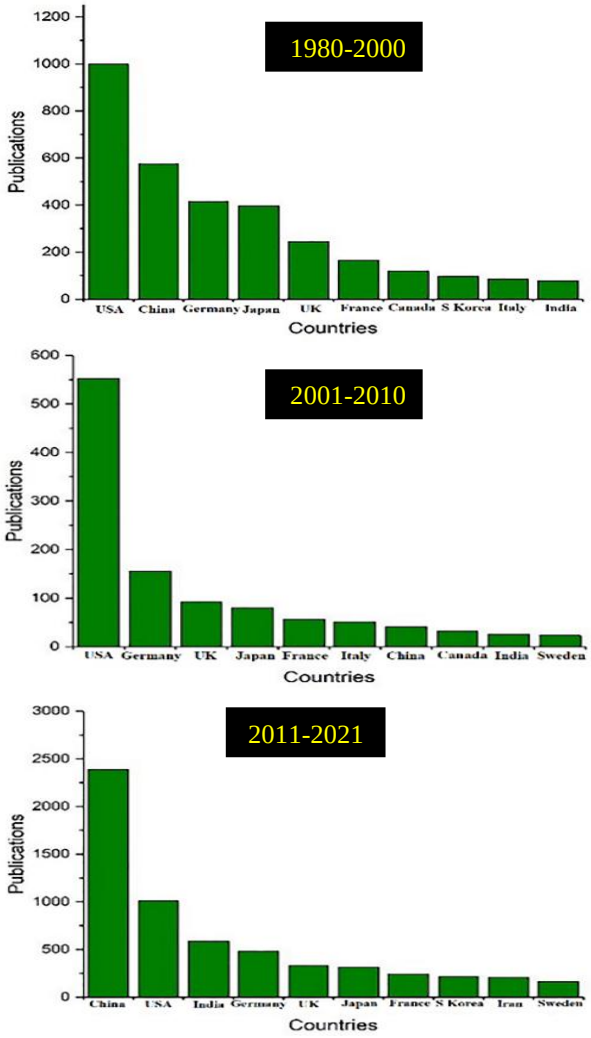


Figure 2. The number of resources produced about TBC in different countries

The United States used to be the leader of scientific production in this field until 2010; however since 2011, China has overtaken the United States' place and moved from seventh place in the years before 2000 to the first place. Iran did not have any articles on the discussed subject until 2000 but after 2001, it had acceptable growth until it reached the ninth rank in 2011.

As observed in Figure 2, between 1980 and 2000, a majority of the articles were published in the United States of America, followed by China and Germany. From 2001 to 2010, China occupied the second place, and Germany and Japan maintained their upward trend and took the third and fourth places, respectively. However, between 2011 and 2021, China, the United States, and India were in the top three countries producing science and have been active in this scientific field of surface engineering, indicating the great attention of these countries to the energy field and increasing productivity in the last decade. England and Japan are

other active countries in this field. Iran has also reached the top ten science-producing countries in this field in the last decade, indicating the sustainable development and training of excellent experts in this field.

In order to properly examine the growth rate of the number of articles in each country, an index called Compound Annual Growth Rate (CAGR) [30] is used, the results of which are shown in Figure 3. The years 2000 and 2010 were selected as the time origin, and the present time is chosen as the end of the analysis period.

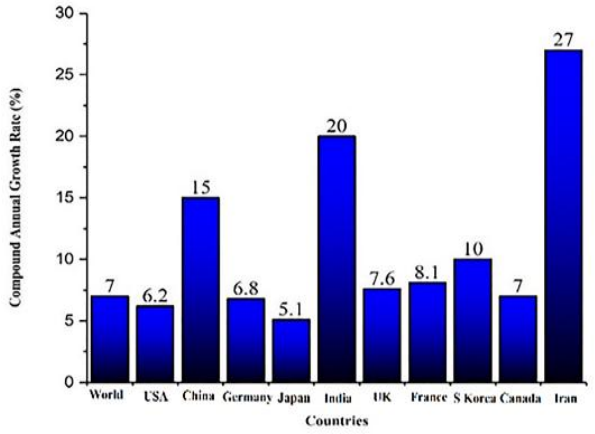


Figure 3. The compound annual growth rate of the ten most active countries in TBCs from 2000 to 2021

According to the observations, the United States has published a high number of articles; However, compared to the past, the process of producing articles in America in this field has slowed down. Between 2001 and 2010, the number of articles was under 200 while between 2011 and 2021, this number increased up to nearly 1000. However, other countries such as India, China, and Iran showed a high annual growth rate. In this regard, Iran can be considered a leading country producing many articles in a short period of time followed by India and China. This shows Iran's progress in gas turbines and related sciences. Publishing articles about the gas turbines, such as TBCs, shows the country's attention to industries related to gas turbines, such as aerospace, gas transmission, and power plants. Paying attention and spending time on scientific projects in the field of gas turbines shows both considerable interest to and a measure of progress in that field, thus promising the efficiency of these industries.

As mentioned earlier, to rank the leading countries and their connections with each other in the field of TBC research, Scopus database data and VOSviewer software were used. Among the 212 active countries in this field, only 33 have authored more than 30 titles. The relationship between these countries is shown in Figure 4.

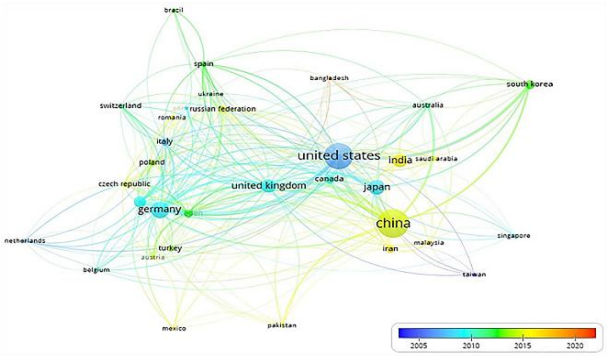


Figure 4. The map of the countries that are active in the field of TBC and their research cooperation with each other

The circle size of each country shows the number of publications relatively while the thickness of the communication lines indicates the strength of communication between countries. The color changes indicate the annual average of the article publications which at the end, shows the distance between the two countries and the proximity of the researchers of the two countries. The United States and China are the leading countries while other countries such as Germany, Japan, and England have either started their activities in recent years or have reduced the amount of their research over time.

While checking the communication network among the keywords in articles about thermal barrier coating, 37739 unique words were found only 28 of them from this collection were repeated at least 500 times. Then, the following result was obtained (similar words were removed). In Figure 5, the size of the circles is indicative of the repetition of the words as well as the lines of connection between the two words. The colors also indicate the year. According to the subject under study, the words Plasma Spraying, Thermal Barrier Coating, and Coatings have been repeated numerously. As a result, these words have a larger circle than the rest. Among the types of coatings, Zirconia, Yttria Stabilized Zirconia, and Alumina have been more critical, showing that these coatings with the Plasma Spray method are the most used in industry and research works.

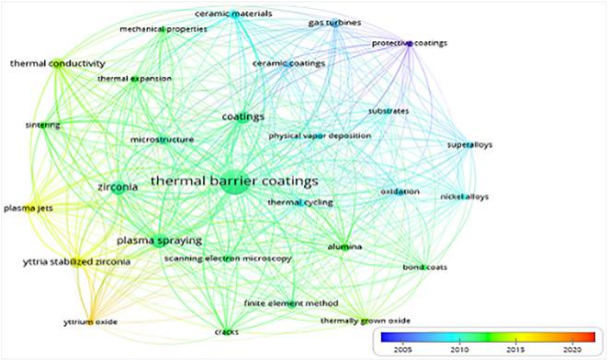
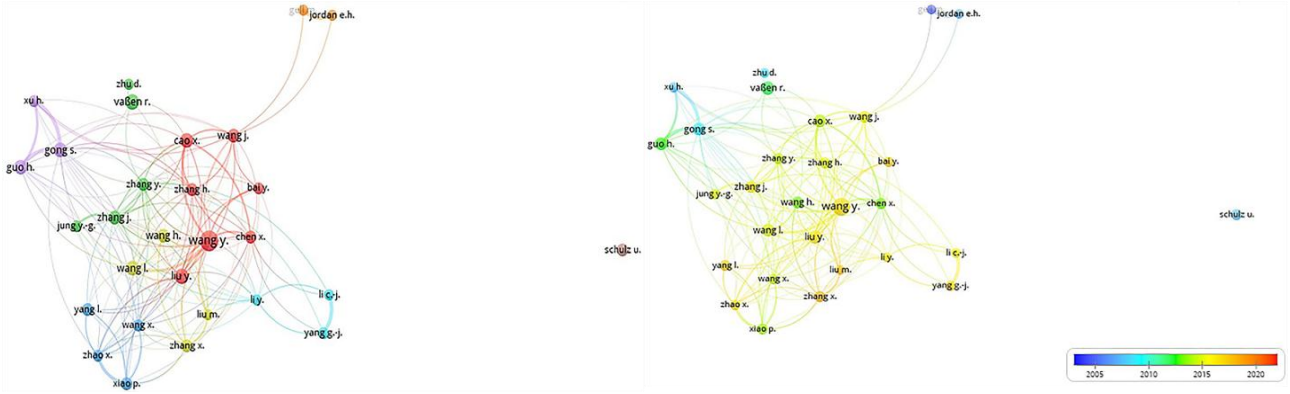


Figure 5. Network of frequently used words in TBC

The network between researchers is drawn in Figure 6(a) with more than 70 titles of authorship based on the research groups (each color represents the relationship of people with each other), and Figure 6(b) is drawn based on the publication year. Out of 16899 authors, 29 researchers have authored more than 70 titles. The most communication network with 19 researchers is related to a researcher named Amy Wang. Some centers and universities that are active in the field of thermal barrier coating are shown in Figure 7. As observed, some centers such as NASA, the German Air Force, and the Oak Ridge National Laboratory were active before 2000. However, academic and research centers and academic centers have taken over most scientific production in this field since 2016.



(a) **(b)**

Figure 6. The communication network of researchers according to the (a) research groups and (b) publication year

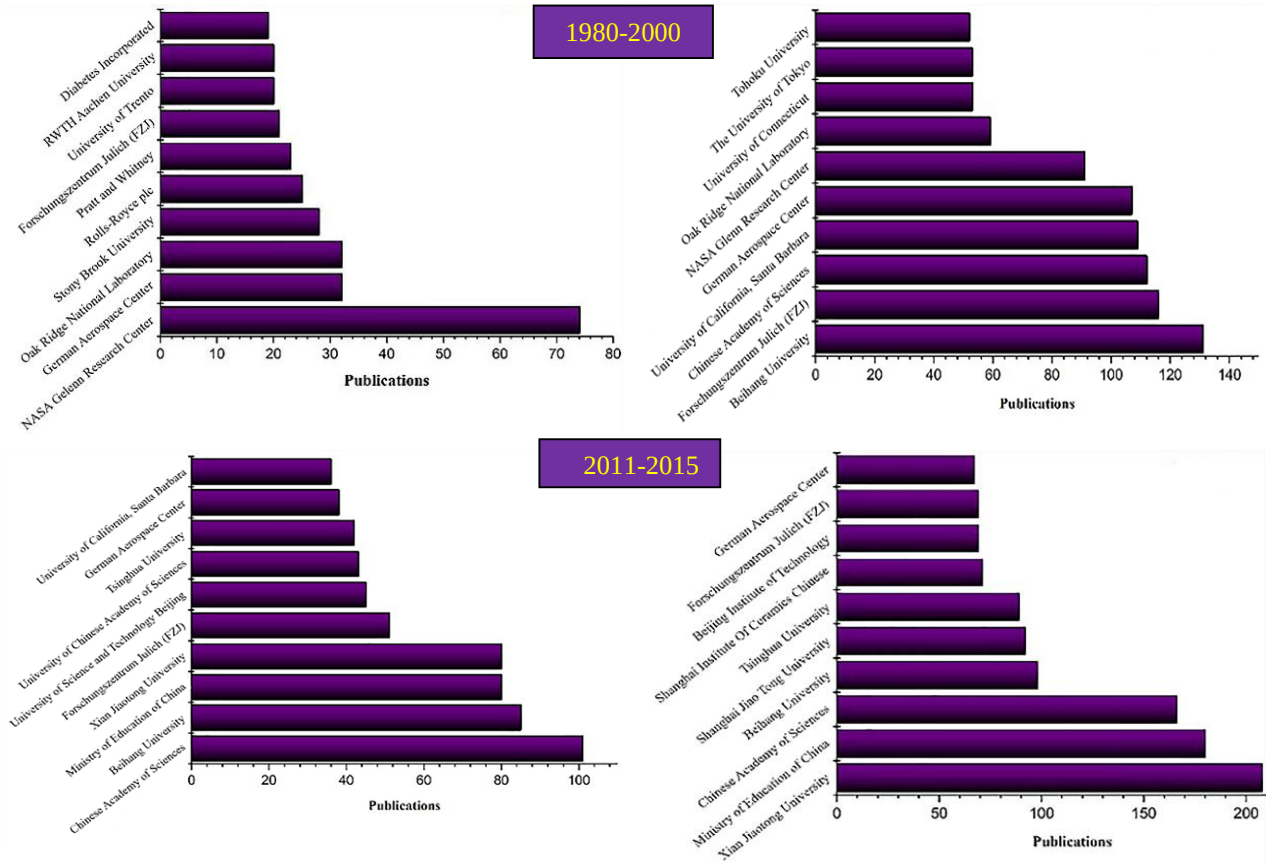


Figure 7. Active centers that conduct research in thermal barrier coatings in different time frames

4. CONCLUSIONS

The following results can be obtained from the current research:

1. In recent years, TBCs have drawn considerable attention which is more tangible in developing countries than the developed ones.
2. In the beginning, the science production rate in TBCs was high in the United States, Germany, and England, and this growth was at the highest level in China, the United States, and India.
3. China has gained the highest number of articles by publishing numerous articles and has reached the top position with a stable trend. Iran has also the highest position in compound annual growth rate. This issue shows the attention of these two countries to TBCs.
4. However, compared the past, the process of producing articles in America in this field has slowed down. Between 2001 and 2010, the number of articles was under 200 titles while between 2011 and 2021, their number increased up to nearly 1,000.
5. Publishing articles in the fields related to gas turbines, such as TBCs, shows the increasing attention of these countries to the industries related to gas turbines such as aerospace, gas transmission, and power plants. Paying attention and spending time on scientific projects in the field of gas turbines shows the considerable attention and a measure of progress in that field, which can also be found in the efficiency of these industries.

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