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A Bibliometric Analysis of the Global Trend of Residual Stress Induced by WAAM Process and Stress Relief Heat Treatment

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ABSTRACT

Gathering data from previous research and incorporating it into a scientometrics investigation can provide valuable insights into a particular area of study. Wire Arc Additive Manufacturing (WAAM) is currently popular for producing customized metal products quickly. Despite this, there have been lack of studies on implementing stress relief heat treatment after the manufacturing process to reduce residual stress in the resulting parts potentially. This paper represents the first bibliometric analysis study focusing on the application of stress-relief heat treatment as a post-processing method for wire arc additive manufacturing (WAAM). Given the exploratory nature of this research, it is expected that future investigations will continue to delve into these areas, ultimately contributing to a better understanding of the effects of stress-relief heat treatment on the additively manufactured materials.

1. Introduction

Wire arc additive manufacturing (WAAM) uses wire as deposited material and an electric arc as a heat source which is like GMA (Gas Metal Arc) welding process. With the continuous development and improvement of manufacturing equipment systems and software algorithms, Wire Arc Additive Manufacturing is gradually applied in aerospace, marine, mining machinery, automobile, mould, and various industrial manufacturing fields. Using this method most suitable to create large design taken from previous study [1-4]. Previous study stated common and serious defect usually occur in WAAM are residual stresses and distortion, tensile residuals have detrimental effects and can cause fractures and deformation due to crack propagation [5-8]. Based on Scopus database the study involves residual stress induce by WAAM keep on increasing starting 2011 till 2022 as in Figure 1.

Figure 1 indicates that research in the field of wire arc additive manufacturing (WAAM), particularly studies related to residual stress, is still developing and attracting increased attention

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from scientists and the academic community. WAAM is a complex process that depends on several variables, including heat buildup, interlayer temperature, and the quality of the previous layer's deposition, all of which have an immediate impact on the stability of the deposition. Ongoing research in this field is recommended to further understand the effects of residual stress on the mechanical properties of additively manufactured materials. Previous studies have explored various methods for mitigating residual stress, including stress relief heat treatment and post-processing techniques [9, 10]. An examination of articles available in the Scopus database showed a decline in the number of publications when certain keywords were combined.

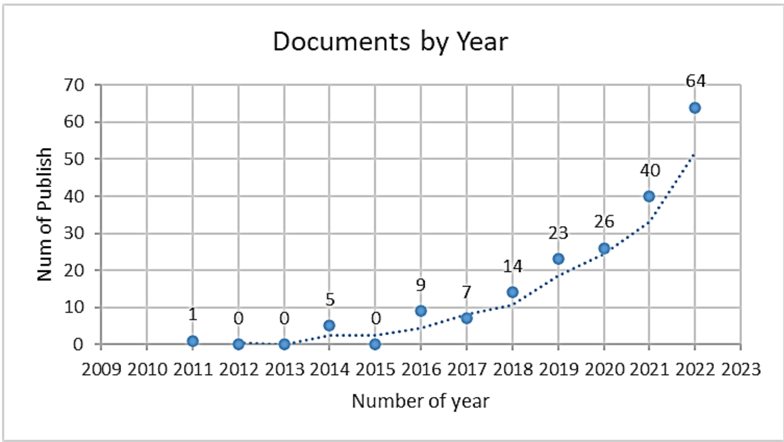

Fig. 1. Publish article of WAAM and residual stress 2011 to 2022

Specifically, when searching for articles using the combined keywords "wire arc additive manufacturing, residual stress, and stress relief heat treatment," only two articles were identified. Both of these articles were published within the timeframe spanning 2011 to 2022 (Table 1). Using less-explored knowledge about stress relief heat treatment, which has received increased attention over the last decade, can be a relevant strategy. Stress relief heat treatment has the capability of improving residual stress and removing impaired characteristics such as ductility taken from previous study [11-13]. Recent studies have explored various methods for mitigating residual stress, including stress relief heat treatment and post-processing techniques. Ongoing research in this field is recommended to further understand the effects of stress relief heat treatment on the residual stress of additively manufactured materials [14-16].

Table 1
Publication based on Scopus database (2011 to 2022) using keyword wire arc additive manufacturing, residual stress, and stress relief heat treatment

Keyword	Publication 2011 - 2022
Wire arc additive manufacturing (WAAM)	2037
Residual stress	59317
Heat treatment	157445
Stress relief (SR) heat treatment	579
Residual stress + SR heat treatment	207
WAAM + residual stress	189
WAAM + residual stress + SR heat treatment	2

1.1 Significant of Study

The purpose of this paper is it to find the current trend on WAAM with application of stress relief heat treatment as post process that could leads to reducing residual stress. Residual stress leads to detrimental effects and can cause fractures and deformation due to crack propagation taken from previous study [6, 7, 17]. Moreover, eliminating residual tensile stresses through stress relief treatments is crucial for improving ductility and improve hardness taken from previous study [15, 18, 19]. Based on Table 1 shows the gap of this related topic and only 2 study were done.

2. Literature Review

Several publications were issued in discussing of wire arc additive manufacturing (WAAM) related to residual stress and stress relief heat treatment. Most of this previous study uses other type of additive manufacturing method such as SLM and LMD [6, 11, 12, 14, 15].

2.1 Residual Stress

Additive manufacturing processes have been plagued by residual stress, which can adversely affect the mechanical properties of the end product. Researchers have employed various techniques to mitigate this issue, such as tweaking the process parameters or incorporating additional steps into the design stated from previous journal [16-18].

Residual stress is primarily caused by the heat input during the process, and it is influenced by heat dissipation and restraint conditions. Generally, residual stress decreases with an increase in energy per unit length. Recent studies have shown that higher heat input during WAAM significantly reduces residual stress [7]. The heat input during additive manufacturing also affects the microstructure growth, which, in turn, affects the material's mechanical properties stated from previous study [20]. Due to an increase in temperature, residual stress occurs. As the temperature increases, the yield stress value decreases, resulting in a decrease in value with each new layer added. This decrease produces lower longitudinal stress values based on previous study [21]. The microstructure condition of the filler affects the residual stress during the cooling process. Using XRD, the proportion of austenite relative integrated intensities peak can be quantified, which reduces strains by 67% and residual stresses by 40% in a three-phase microstructure (austenite, ferrite, and martensite) taken from previous study [22]. When the cooling rate is insufficient to achieve martensite formation, but carbon diffusion and pearlite development are prevented, austenite transforms into a bainitic structure. This change occurs as the structure’s density increases and the martensitic structure decreases farther from the interface taken from previous study [23, 24].

According to a simulation study, adjusting the trend of each layer’s parameters can optimize individual parameters for better results. To reduce residual stress, it’s recommended to increase voltage, decrease welding speed, and maintain a constant current in each layer stated from previous study [25].

2.2 Stress Relief Heat Treatment

The addition of heat treatment during the post-processing stage of metal production is a common practice to enhance its hardness and strength. This is achieved by mitigating the microstructural properties that cause high dislocation density through heat treatment. Employing stress relief heat treatment in this process helps prolong the cooling process, which in turn increases strength and reduces stress.

Additionally, it was observed that all specimens that underwent stress relief post-treatment displayed a significant decrease in residual stress when compared to the original as-built specimen taken from previous study [26]. The fatigue performance was significantly improved by the stress-relief heat treatment as it caused a change in the microstructure and led to the release of residual stresses. The enhancement in the strength and ductility can be attributed to this improvement stated on previous study [15]. At a slow pace of solidification, the transformation of austenite from ferrite is restricted stated on previous study [27]. The diffusion limit of elements constrains the reaction as the temperature decreases, thereby retaining some ferrite in the microstructure. A reduction in the non-equilibrium phase α is achieved through annealing heat treatment, leading to improved corrosion behaviour. The decline of α phase, relief of residual stress, and finer grain collectively contribute to better corrosion resistance stated on previous study [16].

The stress relief heat treatment applied demonstrated that the stress-relieved samples under alternative conditions had similar grain shape and sub grain structure as the industry-standard stress-relieved samples. In addition, the alternative condition samples showed shorter and more equiaxed grains with random orientations taken on previous study [28]. By utilizing a low temperature and extending the holding time during heat treatment, the temperature difference between the treated area and its surroundings is reduced. Consequently, the difference in contraction after cooling becomes minor, leading to a more uniform distribution of stresses as compared to the pre-treatment state stated on previous study [29].

2.3 Finite Element Analysis

The Finite Element Method, also known as FEM, is a numerical mathematical technique used in Finite Element Analysis (FEA) to simulate physical phenomena. FEM is widely used in mechanical engineering and many other fields. In an investigation of EBM additive manufacturing, FEM is used to determine the fatigue connection between the applied stress amplitude and the maximum number of repetitions that the material can withstand stated on previous study [30]. Finite Element Analysis (FEA) plays a crucial role in predicting deviations from the original design, optimizing manufacturing parameters and meeting design standards taken on previous study [31].

A study used finite elements to evaluate the effect of idle periods on interpass temperature for a 20-layer WAAM single-bead wall [32]. Although simulating real size metal parts using CPU is not feasible, FEM simulation can help in understanding the physics of the process stated on previous study [33]. For instance, the simulation process in Simufact welding-6.0 with selected process parameters and inert gas can help in identifying the weld parameter that influences beads, taking into account boundary conditions stated on previous study [34]. However, to reduce computation times, simplified models based on empirical laws are mostly used, which require input parameter calibration with experimental data stated on previous study [2].

The predictive capabilities of FEM analysis extend to a wide range of applications, including the assessment of mechanical properties and structural stability in adhesively bonded joints, as well as the behaviour of 3D-printed parts under varying parameters. Additionally, researchers in both educational and industrial settings can leverage FEM analysis to study mechanical strength, enabling them to optimize parameters, produce parts, and generate computational models with greater accuracy stated on previous study [35].

3. Methodology
3.1 Bibliometric Analysis

The aim of this paper is to ascertain the worldwide research emphasis on the influence of heat treatment for stress relief on residual stress in wire arc additive manufacturing (WAAM). For this objective, information from the Scopus database covering the years 2011 to the present was collected. Using a search approach, the study looked for published studies to examine new developments in this field. The results of the search show that there is increasing interest in learning about and reducing residual stresses in WAAM, with a focus on how different process parameters and post-processing methods, like heat treatment for stress relief, affect residual stress and the mechanical characteristics of additively manufactured components. The research landscape in this field is dynamic, with ongoing studies aiming to advance the understanding of residual stress management in WAAM and its implications for the performance of manufactured parts.

This study aims to identify the research direction in wire arc additive manufacturing, specifically for stress relief heat treatment as a post-processing technique. It also aims to optimize the stress relief heat treatment parameters as a post-processing method using collected data. The study intends to provide a deeper analysis of research trends, productivity, and scientific connections.

However, the normalization process can be challenging, and different approaches have their pros and cons [36]. Bibliometric studies are increasingly being used for research assessment, and the use of bibliometric indicators is strongly methodology-dependent. Despite the challenges, bibliometric analysis offers additional data statistics, including author, affiliation, and keywords, and has become an important research method for assessing national and international research productivity, international cooperation, citation analysis, research trends, and development taken on previous study [37]. The field of bibliometric analysis is rapidly evolving, and ongoing research aims to find the most fair and unbiased approach to appraise scientists, institutions, and journals stated on previous study [38].

The study conducted a bibliometric literature analysis, focusing on key factors such as descriptive (year of publication, subject categories, journal counts), relational (collaborations among authors, countries, institutions), and qualitative (citations, impact factors) terms. The analysis was based on publications containing the main keywords "wire arc additive manufacturing, residual stress, stress relief heat treatment" in their titles or abstracts. The data were retrieved from the Scopus database in December 2023, covering the period from 2011 to 2022. The study's approach and the use of bibliometric methods were intended to contribute to a higher level of analysis of research trends, productivity, and scientific connection patterns across different fields. Microsoft Excel was used for the bibliometric analysis, as it offers various features to assist with this type of analysis.

4. Results

According to data from the Scopus database, the number of publications related to wire arc additive manufacturing (WAAM), residual stress, and stress relief heat treatment has been steadily increasing over the years. Figure 2 illustrates this trend in scientific publications between 2011 and 2019, indicating that these three topics are worth exploring further. By analyzing the Scopus database using the keywords "wire arc additive manufacturing" and "residual stress," we found 189 publications on the subject, and this number has continued to grow each year. Between 2011 and 2022, the number of publications related to WAAM and residual stress increased by 99.69% and 36.07%, respectively. Figure 2 shows a linear increase, suggesting a steady growth rate of publications. We also calculated the relationship between x and y for each subject, with coefficients of determination indicating that the linear regression lines were highly consistent with the actual results. The relationship between x and y was $y = 236.28x + 3407.5$ ($R^2 = 0.9023$) for residual stress, $y = 1.0402^{e0.5757x}$ ($R^2 = 0.9238$) for WAAM, and $y = 4.9126x + 16.318$ ($R^2 = 0.8209$) for stress relief heat treatment. These findings suggest that further research in these areas could be valuable.

When conducting a bibliometric analysis of scientific publications, the type of publication is a crucial factor to consider. From an academic perspective, publication type is a vital criterion for both professional advancement and incentives. Based on the data, approximately 68% of publications were classified as articles for WAAM, with a total of 130 publications related to residual stress. Conference publications were the next most common type, with 35 in total, followed by reviews with 20 publications. The least common publication types were book chapters and conference reviews, with only two of each documented (refer to Table 2).

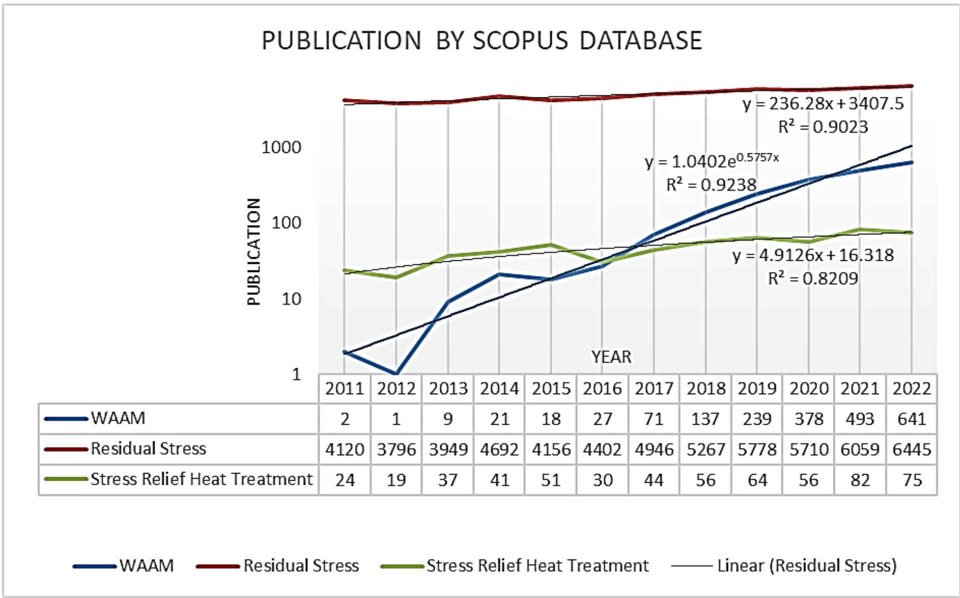

Fig. 2. Trend in publish article of WAAM, residual stress and stress relief heat treatment 2011 to 2022

Table 2
Types of published documents (2011–2022)

Document type	Documents (WAAM)	Documents (WAAM + Residual Stress)	%
Article	1583	130	68.8%
Conference paper	306	35	18.5%
Review	62	20	10.6%
Book chapter	45	2	1.1%
Conference review	32	2	1.1%

According to Figure 3, the countries with the highest participation and productivity in WAAM publications are China, India, and the United States. China takes the lead with an impressive 816 publications (18117 citation) related to WAAM between 2011 and 2022. India and the United States follow closely behind with 212 publications (3054 citations) and 176 publications (3452 citations), respectively. The United Kingdom and Germany also show strong participation with 169 publications (9213 citations) and 166 publications (3252 citations). Notably, China also dominates the h-index, occupying the top three positions for WAAM keywords, indicating high-quality publications. The countries with the highest h-index overall are China, the United Kingdom, and the United States. In terms of subject area, most papers are focused on Engineering, followed by Material Science, Physics and Astronomy, as shown in Table 3. Interestingly, the topic of WAAM is also documented in other subject areas, including Social Sciences (4), Agricultural and Biological Sciences (20), Arts and Humanities (1), and Pharmacology, Toxicology, and Pharmaceutics (1), demonstrating its interdisciplinary nature.

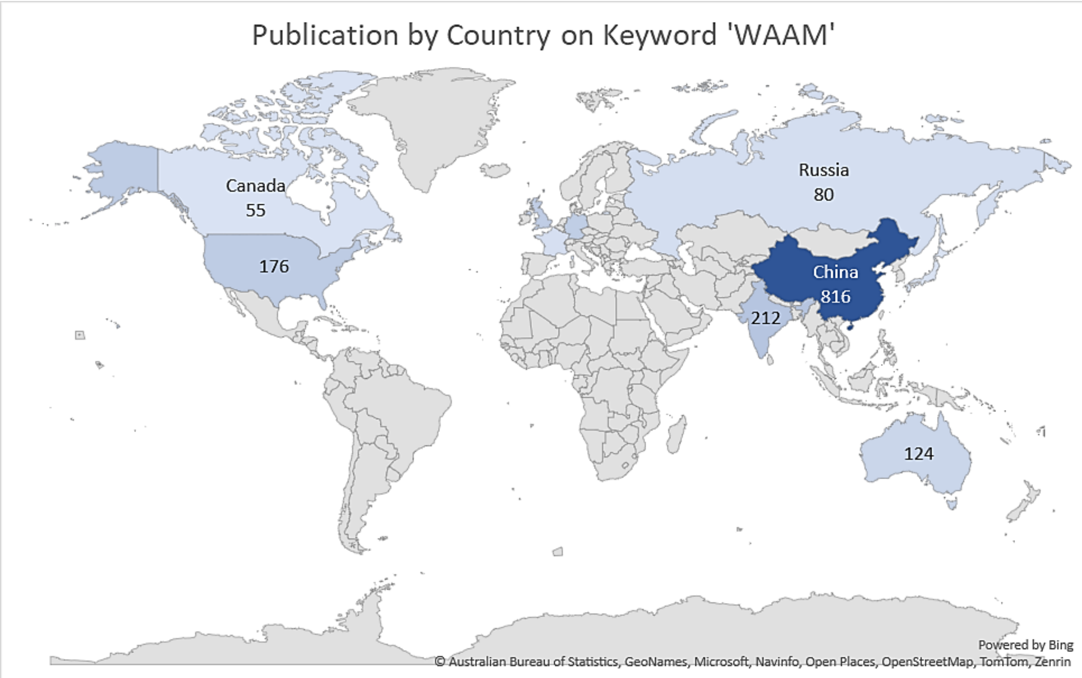

Fig. 3. Number of publications by country

Table 3
Subject area of published documents (2011–2022)

Subject area	Documentation
Engineering	1528
Materials science	1273
Physics and astronomy	493
Computer science	340
Business, management and accounting	106
Decision sciences	98
Mathematics	96
Chemical engineering	83
Energy	48
Chemistry	47
Environmental science	16
Earth and planetary sciences	15
Multidisciplinary	7
Biochemistry, genetics and molecular biology	4
Social sciences	4
Agricultural and biological sciences	2
Arts and humanities	1
Pharmacology, toxicology and pharmaceutics	1

In Figure 4, we can see the leading publishing journals, with three standouts being Additive Manufacturing with 101 publications, the International Journal of Advanced Manufacturing Technology with 98 publications, and Metals with 91 publications for WAAM. Based on the cite score analysis for 2022, Additive Manufacturing boasts the highest score with 17 on cite score and 11 on impact factor. The majority of publications (over 92%) were in English, with only 7% in Chinese and 1% in German. Table 4 displays the top ten institutes' statistical information based on the number of papers using WAAM keywords. Among the top ten, half were from China Institution, followed by the United Kingdom and Australia.

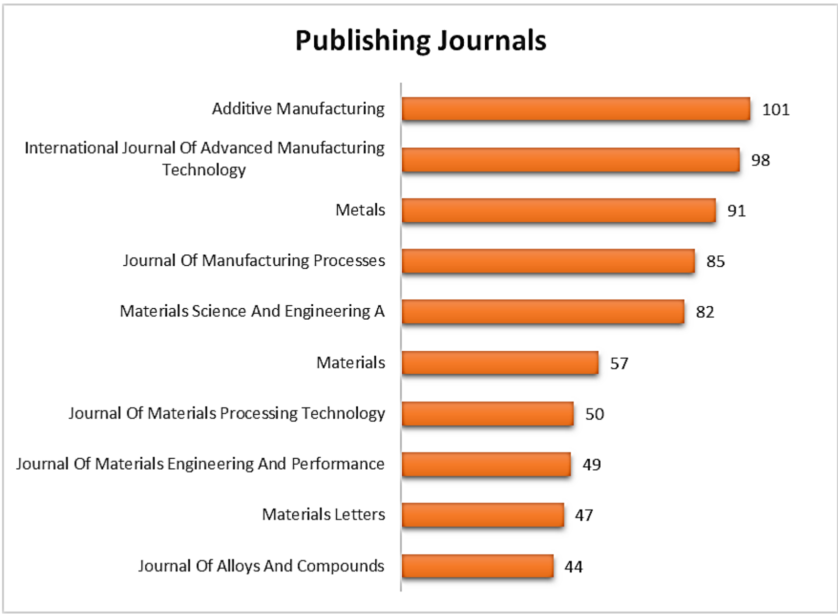

Fig. 4. Top publishing journals from 32 publisher

Table 4
Top 10 Institute related to paper under WAAM Keyword

Affiliation	Paper publishes
Cranfield University	113
University of Wollongong	93
Huazhong University of Science and Technology	78
Ministry of Education of the People's Republic of China	62
Harbin Institute of Technology	59
Beijing Institute of Technology	48
Tianjin University	48
Beijing University of Technology	41
Shanghai Jiao Tong University	40
Xi'an Jiaotong University	37
Nanjing University of Science and Technology	34

Table 5 presents a summary of the most frequently used words in paper titles. From 2011 to 2022, the top words used in publications for WAAM were "3D printer" (1495), "Finite Element Method" for Residual Stress (6985), and "Residual Stresses" (179) for Stress Relief Heat Treatment, excluding keyword searches. Analyzing keywords in research papers can provide valuable insights into ongoing and future trends in science and engineering.

Based on this discussion and analysis, there are two study related to WAAM and stress relief heat treatment in which adding this method to reduce residual stress are as below:

i. This research focuses on adding or repairing metallic materials using wire feeding and different heat sources. After refurbishing the materials, they undergo heat treatment to alleviate post-deposition stress. A comprehensive analysis of three-dimensional displacement mapping is conducted using digital image correlation to understand the geometrical distortion present in the substrate based on previous study [18].

ii. This study explores methods such as heat treatments and hot isostatic pressing (HIPing) to enhance material strength. Slow cooling rates during processing can achieve a balanced microstructure, which maximizes both strength and ductility. HIPing reduces gas porosity, but has little effect on strength or ductility based on previous study [14].

Table 5
Keywords used in publication (2011–2022)

Keyword WAAM		Keyword residual stress		Keyword SR heat treatment	
3D Printers	1495	Residual stresses	24725	Stress relief	364
Additives	1357	Residual stress	10893	Heat treatment	277
Wire	834	Finite element method	6985	Residual stresses	179
Wire arc	661	Cracks	5388	Microstructure	130
Additive manufacturing	611	Microstructure	4161	Welding	90
Microstructure	581	Welding	3901	Welds	79
Welding	173	Titanium Alloys	2232	Grain boundaries	38

5. Conclusion

The analysis of scientometrics on Wire Arc Additive Manufacturing (WAAM) with regard to Residual Stress and Stress Relief Heat Treatment has made significant contributions based on a bibliometric study. The data extracted from the Scopus database was used to analyze publication characteristics such as quantity and quality over the past decade. This study is the first to report on global trends related to WAAM and Residual Stress, and Stress Relief Heat Treatment. In this bibliometric analysis, the main keywords used are "Wire Arc Additive Manufacturing" and "Residual Stress," along with the keyword "Stress Relief Heat Treatment." The findings obtained from this analysis provide valuable insights for future research. The most notable outcomes of this study are the identification of trends and patterns related to these subjects:

i. It was discovered that there are 2037 publications containing the keywords "Wire Arc Additive Manufacturing". Additionally, 189 papers containing the keywords "Residual Stress" were identified. Finally, 2 publications by including the keyword "Stress Relief Heat Treatment", the total number of papers found was updated.

ii. The prominence of the article type as the dominant category in terms of the type of publication has become increasingly significant in academic discourse.

iii. According to the total publication criteria, China and India are the most productive countries.

iv. Engineering emerges as the preeminent subject area for research. However, it is noteworthy that this domain shares a symbiotic relationship with other fields such as Agricultural and Biological Sciences, Arts and Humanities, and Pharmacology, Toxicology, and Pharmaceutics, which are also germane to this topic.

v. The keywords that have garnered the most attention in the field of additive manufacturing and materials engineering pertain to the implementation of 3D printing for wire arc additive manufacturing, the utilization of the Finite Element method for the analysis of residual stress, and the application of Residual Stresses in the context of stress relief heat treatment.

vi. It is noted that more than 92% of the publications were published in the English language.

vii. The publication journal that falls under the category of Additive Manufacturing has taken the foremost position, with a total of 101 publications and an impact factor of 11, thereby highlighting its significance in the field of research and academia.

viii. In order to advance the related research, there is a need for an improved interpretation of bibliometric analysis. The development of more comprehensive knowledge regarding this type of research would enable the achievement of a higher degree of accuracy on this subject.

Although stress relief heat treatment is advantageous in reducing residual stress, it faces certain challenges in certain applications where further improvements are needed. Wire arc additive manufacturing applications, in particular, can benefit from a simulation approach as a potential future method. It is anticipated that the number of studies investigating the relationship between stress relief heat treatment and these applications will increase in the upcoming decade.

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