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Top-cited articles in the field of tribology : A bibliometric analysis

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The aim of this study is to identify and analyze the characteristics of the top – cited articles in the field of tribology based on the Science Citation Index Expanded (SCI – EXPANDED). The parameters are: publication years, journals, Web of Science categories, authors, institutions, countries, and citation life cycle curve. Y – index is used to evaluate the publication characteristic of authors of top – cited articles. Three kinds of citations: citations in 2013, total citations, and citations in publication year were employed to characterize the top – cited articles in tribology. Top three journals are Surface & Coatings Technology, Wear, and Tribology International. IBM Corporation was the most active institution on tribology research. The G7 countries have dominated this research field in terms of number of publications. Some of the keywords such as "tribology", "tribological", "wear", "friction", "diamond – like carbon", "carbon or DLC", "coatings", "materials", and "composite" were ranked among the top keywords in all the three types of keywords analysis : Words in titles, author keywords, and *KeyWords Plus*.

Keywords: *Citation Analysis, Tribology, Science Citation Index – Expanded, Y – index*

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1. Introduction

Top-cited articles can provide interesting and useful insights into which authors, institutions, countries, articles, and topics are influencing as well as motivating the research field over time [1]. The best article can be considered by the number of citations received in the peer – reviewed journals [2]. Top – cited articles also called as highly cited articles [3], classic articles [4], and most frequently cited articles [5] which represent the most significant

developments in a specific research field. Citation of a published work is one of the parameters considered in the analysis of relevance and importance of scientific contributions [6]. Citation rates using data from the Web of Science is now a popular method to evaluate the impact on the scientific community of individual scientists as well as research institutions and countries [7]. Citing the original article not only conveys respect for the work of the authors who presented their research for critical appreciation, but also adds to the knowledge base through further discussion [8]. Citations are abbreviated alphanumeric expressions that acknowledge the relevance given by the author to the work of peers on a subject of discussion in which the citation appears. Indeed, the well – known adsorption isotherms had high citation histories in adsorption field [9]. The number of times a publication is cited can be an indication of its relative impact in a given research field [10 – 11]. A large number of citations for a paper are of paramount importance to the journal as well, as the more cited an article from a particular journal, the greater the impact factor of the publication [12]. It can imply that a publication is widely read and that others in the field view it as worthy of continued discussion [13]. Citation analysis is also a feasible tool to comprehensively recognize the research advances in the past and future research trends in a specific field [14]. Citation analysis involves the construction and application of a series of indicators of the "impact", "influence", or "quality" of scholarly work, derived from citation data, i.e. data on references cited in footnotes or bibliographies of scholarly research publications [15]. A high citation count is an indication of the influence of specific articles [16]. Characterization of high impact studies may help future investigators to tailor their research interests and pursuits to the particular areas [17]. A review of the top – cited articles in a scientific discipline can identify areas of research that are well established and those in need of further development, and may, as a result, inform and direct future research efforts [18].

The word "tribology" was coined by Jost in a report in 1966 as a composition of two Greek words tribos and logos. Tribology is the science and technology of interacting surfaces in relative motion and the practices related thereto [19]. It is multidisciplinary in nature which includes physics, chemistry, metallurgy and engineering [20]. Tribology plays an important role in diverse technological areas of components, assemblies or products, manufacturing process, construction, exploration, apart from mechanical transmission (Bearings, clutches, brakes), energy savings (gears, drives, actuators), material science (cutting, drawing, sealing), transportation field (wheel/rail, tyre/road, pipelines) and information technology (computer heads, slip – ring assemblies, audio – video sets) [21]. Tribology also plays important role in nuclear power generation in terms of enrichment of uranium fuel to the operation of power plant [22]. The areas of possible applications of tribology are being expanded from conventional engineering machines and manufacture to MEMS and hair conditioners in the twenty – first century [23]. According to the reports, £550 million per annum (in 1966 terms) could be saved in industries of the UK by better application of tribology concepts, it was increased to £13 billion (in 1983 terms) of loss due to

tribological causes, about $400 hundred million (in 2006 terms) could be saved in China through industrial application of tribology and about savings of $120 billion per year is possible in the USA by reducing friction and wear in engine [20, 24 – 26]. Sub – disciplines of tribology have been emerged at the interface of various scientific disciplines, like nano-tribology/microtribology, biotribology and green tribology/ecotribology [26, 27].

A number of studies was focused to analyze top – cited articles in various branches of universe ranging from engineering to science and to medicine, for example materials science [28], thermodynamics [29], chemical engineering [6], environmental science [30], health care science [31], pain [32], and surgery [33].

The aim of the present study was to identify and analyze the characteristics, such as publication year, publishing journal, publication type, authors, institutions, and countries of the top – cited articles in the field of tribology research based on SCI – EXPANDED of Web of Science. In terms of citations of top – cited articles, three kinds of citations: total citations since their publication to the end of 2013, total citations in a recent single year, and total citations in publication year have been employed.

2. Methodology

Bibliographic records used in this study were derived from the Science Citation Index Expanded (SCI – EXPANDED) database of the Web of Science (WoS), the Thomson Reuters (updated on May 21, 2015). Keywords tribolog*, tribosyst*, tribo – syst*, tribo – chem*, tribochem*, tribotechn*, tribo – physi*, and tribophysi* [34] were used in terms of topic (including four parts: paper title, abstract, author keywords, and *KeyWords Plus*) to retrieve the bibliographic records related to tribology research. *KeyWords Plus* supplies additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes in the ISI (now Thomson Reuters, New York) database, and substantially augments title – word and author – keyword indexing [35]. A detailed description of the keywords is provided in Table 1.

Initially, we found a total of 21,361 documents comprising 18 document types, including articles, proceedings papers, reviews, editorial materials, meeting abstracts, notes, letters, corrections, item about an individual, news items, reprints, book reviews, biographical items, book chapters, discussions, correction additions, bibliographies, and abstract of published items. Only the document type "article" was considered for this study.

Two additional filters, total citations since their publication to the end of 2013, TC2013, [9, 36] and the "front page" [8], were employed to retrieve the top – cited articles. Because citations' invariance will not be updated, TC2013 was applied [8]. The articles selected by TC2013 ≥ 100 were deemed top – cited articles. The total number of times an article was cited from its publication until the end of 2013 was recorded as TC2013 [9, 36]. The other filter, the "front page", was used to identify articles with the indicated keywords on their

Table 1

Description of keywords

Keywords	Related keywords
tribolog*	tribological, tribology, tribologically, tribologcal, tribolog, tribologocal, tribologys, tribologie, tribology93, tribologsts, tribologique, tribologry, tribologyl, tribologischen, tribologi, tribologists, tribologists, tribologycal, tribologicaly, tribologkal, tribologicai, tribologist, and tribologic
tribosyst*	tribosystem and tribosystems
tribo – syst*	tribo – system, tribo – systems, andtribo – systern
tribo – chem*	tribo – chemical, tribo – chemistry, and tribo – chemically
tribochem*	tribochemical, tribochemistry, tribochemically, tribochemicaly, tribochem, tribochemische, tribochemischen, and tribochemie
tribotechn*	tribotechnical, tribotechnics, tribotechnologies, tribotechnica, tribotechnicality, TRIBOtechnic, tribotechnological, and tribotechnology
tribo – physi*	tribo – physics, tribo – physical, and tribo – physicochemical
tribophysi*	tribophysical, tribophysics, tribophysically, and tribophysicochemical

"front page" only, including the article title, abstract, and keyword section [8]. Articles that could be found only through KeyWords Plus were excluded. Finally, 165 articles (0.83% of the 19,762 total articles) were selected as top – cited articles. These records were downloaded into spreadsheet software, and additional coding was manually performed using Microsoft Excel 2010 [37].

Articles published after 1997 from Hong Kong were included in China [9]. Articles from Germany and Federal Republic of Germany (Fed Rep Ger) were reclassified as being from Germany [6]. As the corresponding author is labeled as reprint author in the SCI – EXPANDED database, who is identified as the corresponding author [6]. The author is classified as both the first author and the corresponding author for single authored articles [6]. Similarly, the institution is classified as both the first author's and the corresponding author's institution for single authored articles [10]. If one author was assigned as the first author of an article, that article was considered a "first – author article" by that author, and if one author was assigned as the corresponding author of an article, that article was considered a "corresponding – author article" by that author [6]. In terms of country or institution, the term "first – author article" was assigned if the first author was from the country or institution under analysis, and the term "corresponding – author article" was assigned if the corresponding author was from the country or institution under analysis. TP, FP, and RP are the numbers of total articles, first – author articles, and corresponding – author articles for a country, an institution, or an author, respectively [37].

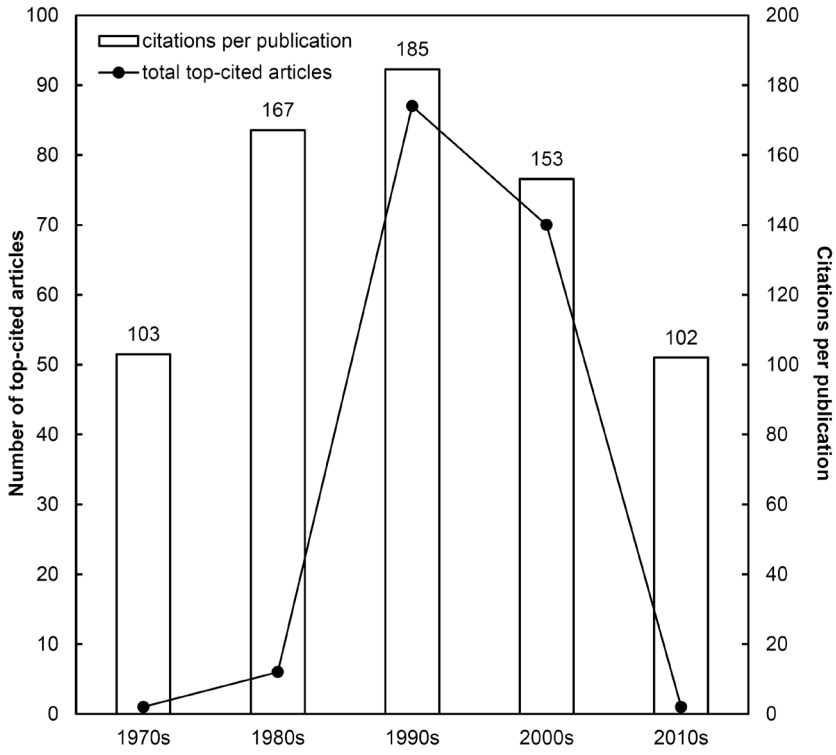

Figure 1

Number of articles and citations per publication by decade

3. Results and Discussion

3.1. *Distribution of top – cited articles*

A total of 165 articles are identified as top – cited articles (articles received greater than or equal to 100 citations from its time of publication through 2013) which were published between 1971 and 2011. Figure 1 illustrates the number of top – cited articles and citations per publication by decades which show that most of the top – cited articles were published during 1990s and 2000s. Highest number of top – cited articles was published in 2001. There were no top – cited articles in the years 1972 – 84, 1988, 2009, and 2010. One reason is that the recent significant growth in numbers of journals and papers which may be contributed to the increase in top – cited articles [38]. As more articles are being published, there are more chances to be cited, and hence, a greater likelihood to accumulate citations [32]. In total, 543 authorships were responsible for the 165 top – cited articles and an average number of authors per top – cited article were 3.3 with 18 as the largest number of authors. Similarly, small groups of authors were found in highly cited articles in material science with 3.6 [28] and in chemical engineering with 3.6 [39]. Totally 6,232 references

Table 2

Six core journals

Journal	TP (%)	IF2013	Web of Science category
Surface & Coatings Technology	33 (20)	2.199	Coatings & Films Materials Science Applied Physics
Wear	26 (16)	1.862	Mechanical Engineering Multidisciplinary Materials Science
Tribology International	10 (6.1)	2.124	Mechanical Engineering
Diamond and Related Materials	6 (3.6)	1.572	Multidisciplinary Materials Science
Nature	6 (3.6)	42.351	Multidisciplinary Sciences
Tribology Letters	6 (3.6)	2.151	Chemical Engineering Mechanical Engineering

TP: total number of articles; IF2013: impact factor in 2013

were appended at the end of top – cited articles with an average of 38. On an average of 9.6 pages per top – cited article were used to publish the research findings. Furthermore, it is observed that there was a wide variation in average pages and references per article.

3.2. *Journals and WoS Subject Categories*

Top – cited articles were published in 55 journals. Of these 55 journals, 32 (58%) journals contained only one top – cited article and 10 (18%) journals contained two articles. Fifty – three percent of all top – cited articles were published by six core journals (Table 2). The impact factor (IF2013) of the top six journals lies between 1.572 and 42.351 which shows that the leading journals attracted top – cited publications and also maintains the high IF_{2013}. The Journal *Surface & Coatings Technology* (IF_{2013} = 2.199) published the most top – cited articles with 33 articles (20% of 165 articles), followed by *Wear* (IF_{2013} = 1.862) with 26 articles (16%), *Tribology International* (IF_{2013} = 2.124) with 10 articles (6.1%), and *Diamond and Related Materials* (IF_{2013} = 1.572), *Nature* (IF_{2013} = 42.351), and *Tribology Letters* (IF_{2013} = 2.151), with six articles (3.6%) each. However, top cited articles were also published in journals with low impact factors, for example, *Journal of Tribology – Transactions of the ASME* (IF_{2013} = 0.897), Tribology Transactions (IF_{2013} = 1.081), and *Proceedings of the Institution of Mechanical Engineers Part H – Journal of Engineering in Medicine* (IF_{2013} =1.144). Moreover, three high – impact factor journals were also published the top – cited articles such as *Nature* (IF_{2013} =42.351) with six articles, *Science* (IF_{2013} =31.477) with two articles, and *Nano Today* (IF_{2013} =18.432) with one article.

The top – cited articles were published in the 33 Web of Science subject categories in the science edition. Among these, one third of categories published each one article and one third of categories published the top – cited articles between 2 and 5. Top 11 (33%) categories published the top – cited articles between 6 and 61. The five top categories include multidisciplinary materials science (61 articles; 37% of 165 articles), mechanical engineering (48;

Table 3

Characteristics of the 14 most – productive authors (≥ 4 articles)

Author	Rank (*TP*)	Rank (*FP*)	Rank (*RP*)	Rank (*SP*)
A. Erdemir	1 (10)	3 (4)	4 (4)	2 (2)
B. Bhushan	2 (7)	3 (4)	1 (6)	4 (1)
A. Grill	2 (7)	1 (5)	2 (5)	1 (4)
J.S. Zabinski	4 (6)	N/A	N/A	N/A
W.M. Liu	5 (5)	17 (1)	9 (2)	N/A
A. Matthews	5 (5)	N/A	15 (1)	N/A
A.A.Voevodin	5 (5)	1 (5)	2 (5)	N/A
H. Dimigen	8 (4)	8 (2)	9 (2)	N/A
C. Donnet	8 (4)	3 (4)	4 (4)	4 (1)
I. Etsion	8 (4)	17 (1)	15 (1)	4 (1)
T.E. Fischer	8 (4)	17 (1)	15 (1)	N/A
J. Israelachvili	8 (4)	N/A	N/A	N/A
S. Jacobson	8 (4)	N/A	6 (3)	N/A
A. Leyland	8 (4)	8 (2)	6 (3)	N/A

TP: total top – cited articles; FP: first – author top – cited articles; RP: corresponding – author top – cited articles; SP: single – author top – cited articles; N/A: not available

29%), applied physics (48; 29%), coatings and films materials science (39; 24%), and physical chemistry (15; 9.1%). These five categories published a majority of the total top – cited articles (128 articles; 78% of 165 articles). One thing should be noticed that journals may be classified in two or more categories in WoS, for instance, *Surface & Coatings Technology* was listed in both categories of "coatings and films materials science" and "applied physics". Categories other than engineering and science, such as dentistry, surgery, biology, cell biology, and orthopedics are also visible. It shows the multidisciplinary character of this research field.

3.3. *Most Productive Authors*

Among the 425 authors contributing to 165 top – cited articles, 290 authors (68% of 425 authors) had no first author articles, 306 (72%) authors had no corresponding author articles, and only 118 (28%) authors had both first author articles and corresponding author articles. Table 3 shows the total top – cited articles (*TP*), first – author top – cited articles (*FP*), corresponding – author top – cited articles (*RP*); and single – author top – cited articles (*SP*) of leading authors with at least four top – cited articles. Top three authors of top – cited articles are A. Erdemir from Argonne National Laboratory in the USA with 10 articles, B. Bhushan from Ohio State University in the USA with 7 articles and A. Grill from

IBM Corporation in the USA with 7 articles. Among these 14 authors, two authors such as A.A. Voevodin and C. Donnett published all the articles with first and corresponding author. In addition, A. Grill published the most first author and single – author articles respectively.

The recently developed *Y* – index [11] has been used in numbers of studies to evaluate the performance of highly cited authors, for example, the most – cited articles in chemical engineering [6], the most – cited research articles in the Science Citation Index Expanded [40], the most – cited articles in adsorption research [41], highly cited articles in health care sciences and services field [31], and highly cited articles in materials science [28]. The designation of the first and corresponding author provides a useful method to take account of the multiple authorships [41]. The first author is that person who is responsible for conducting the research work and writing of the research paper [42]. The corresponding author is that person who has substantial contribution to the research in terms of supervision of the planning and execution of the research work and writing of the research paper [43, 44]. The country or institution of the corresponding author might be a home base or origin of a concerned study [11]. The Y – index (*j*, *h*) was applied to evaluate the characteristics of authors of top – cited articles. This index is related to the numbers of first – author publications (*FP*) and corresponding – author publications (*RP*), as defined below [11, 28].

$$j = FP + RP \tag{1}$$

$$h = \tan^{-1}\left(\frac{RP}{FP}\right) \tag{2}$$

An author with a higher *j* has more first – or corresponding – author articles, playing a leadership role. *h* differentiates the nature of that leadership role. Values of $h > 0.7854$ indicate more corresponding – author articles, and values of $h < 0.7854$ indicate more first – author articles. When $h = 0.7854$, the author has the same number of first – author articles and corresponding – author articles. When h = 0, j = the number of first – author articles, and when $h = \pi/2$, *j* = the number of corresponding – author articles. Among the top – cited 165 articles, there was no information about corresponding author for 15 (9.1%) articles. We analyzed 387 authors contributing to 150 top – cited articles (91% of 165 articles) with both first – and corresponding – authors' names in the Web of Science Core Collection.

Figure 2 displays the distribution of the top 15 authors ($j \geq 3$) with *Y* – index. These 15 authors were considered to be the main contributors to the top – cited articles in tribology research, who made the most contribution including conception and design, analysis and interpretation of data and the drafting or reviewing of the article [45, 46]. In the Fig. 2, each dot represents one value that could be one author or many authors when they had the same publication intensity and characteristics. The authors who contributed the most to tribology research were B. Bhushan, A. Grill, and A.A. Voevodin ($j = 10$), followed by C. Donnett and A. Erdemir ($j = 8$). Publication character *h* could help to obtain the different proportion of first author articles to corresponding author articles. It is helpful especially when *j* of authors is too close to distinguish the different contribution of authors. Within these 15 authors, only four authors: B. Bhushan ($j = 0.9828$), A. Leyland ($j = 0.9828$), J. Klein

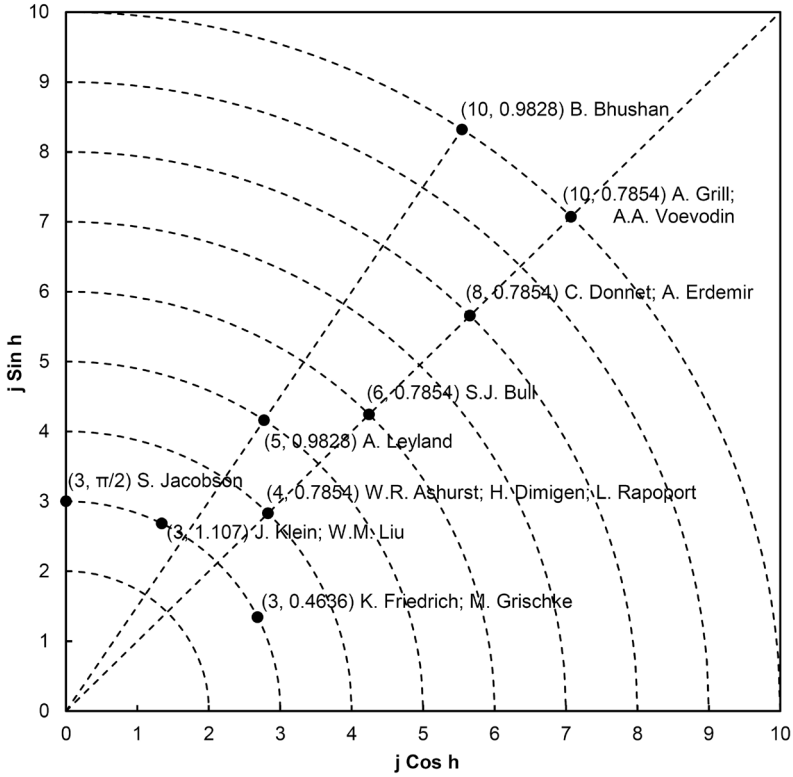

Figure 2

Distribution of the top 15 authors with their *Y* – index values ($j \geq 3$)

(j = 1.107), and W.M. Liu (j = 1.107) had more corresponding author articles than the first author articles. Only two authors: K. Frederich and M. Grischke had more first author articles than corresponding author articles with j = 0.4636. Seven authors on the boundary line owning the same quantity of first author articles and corresponding author articles with h = 0.7854. Only one author S. Jacobson ($h = \pi/2$) has only corresponding author articles and no first author articles. S. Jacobson, J. Klein, W.M. Liu, K. Friedrich, and M. Grischke had the same values of j = 3. Their h values show different publication characters and show Jacobson published more corresponding author articles. Even though, B. Bhushan and A. Leyland had the same values of h = 0.9828, the higher value of j shows that B. Bhushan had higher publication intensity.

3.4. *Distribution of Institutions*

Among the 165 top – cited articles, ten articles had no corresponding author affiliation information and only one article has no any affiliation information in Web of Science. Of the 164 top – cited articles with author affiliations, 101 (62% of 164 articles) were single institution articles and 63 (38%) were inter – institutionally collaborative articles. A small

Table 4

Characteristics of the 12 most productive institutions

Institution	*TP*	*TP R* (%)	*IP R* (%)	*CP R* (%)	*FP R* (%)	*RP R* (%)	*SP R* (%)
IBM Corporation, USA	12	1 (7.3)	1 (6.9)	2 (7.9)	1 (4.9)	1 (5.2)	1 (17)
Argonne National Laboratory, USA	10	2 (6.1)	7 (2.0)	1 (13)	2 (3.7)	2 (3.9)	2 (8.7)
Ohio State University, USA	8	3 (4.9)	2 (5.9)	9 (3.2)	2 (3.7)	2 (3.9)	4 (4.3)
Chinese Academy of Science, China	7	4 (4.3)	3 (3.0)	3 (6.3)	6 (2.4)	5 (2.6)	N/A
ÉcoleCentrale de Lyon, France	5	5 (3.0)	7 (2.0)	4 (4.8)	4 (3.0)	4 (3.2)	2 (8.7)
Universityof California Berkeley, USA	5	5 (3.0)	3 (3.0)	9 (3.2)	4 (3.0)	5 (2.6)	4 (4.3)
Universityof California Santa Barbara, USA	5	5 (3.0)	3 (3.0)	9 (3.2)	7 (1.8)	N/A	N/A
Technion – Israel Institute of Technology, Israel	4	8 (2.4)	21 (1.0)	4 (4.8)	13 (1.2)	11 (1.3)	4 (4.3)
Universityof Hull, UK	4	8 (2.4)	21 (1.0)	4 (4.8)	7 (1.8)	7 (1.9)	N/A
Universityof Kaiserslautern, Germany	4	8 (2.4)	7 (2.0)	9 (3.2)	7 (1.8)	7 (1.9)	N/A
United States Air Force (USAF), USA	4	8 (2.4)	3 (3.0)	24 (1.6)	7 (1.8)	7 (1.9)	N/A
Weizmann Institute of Science, Israel	4	8 (2.4)	7 (2.0)	9 (3.2)	13 (1.2)	11 (1.3)	N/A

TP: total top – cited articles; *IP*: single – institution top – cited articles; *CP*: inter – institutionally collaborative top – cited articles; *FP*: first – author top – cited articles; *RP*: corresponding – author top – cited articles; *SP*: single – author top – cited articles; *R*: rank; N/A: not available

proportion of institutions accounted for a high proportion of top – cited articles which is consistent with earlier studies such as pain research [32]. Table 4 provides the characteristics of top 12 most productive institutions using six indicators [38]: total number of top – cited articles (*TP*), single institution top – cited articles (*IP*), inter – institutionally collaborative top – cited articles (*CP*), first author top – cited articles (*FP*), corresponding author top – cited articles (*RP*), and single author top – cited articles (*SP*). The list was led by IBM Corporation of the USA (12 articles), Argonne National Laboratory of the USA (8 articles), and Ohio State University of the USA (8 articles). Among the top 12 most productive institutions, six are located in the USA followed by Israel (2 institutions) and each one to China, France, the UK, and Germany. IBM Corporation was ranked top in all the indicators except for inter – internationally collaborative articles. The 8th position United States Air Force ranked 3rd in *SP* and 24th in *CP*, which suggested that the scientists affiliated to this organization willing to contribute top – cited articles without collaboration. The institutions Technion – Israel Institute of Technology and University of Hull are ranked 4th in *CP*. However these two institutions were ranked 21st in *IP* which indicates that the scientists affiliated to these institutions prefer to contribute articles with inter – institutional collaboration.

Table 5

Characteristics of the contributing countries

Country	*TP*	*TP R* (%)	*IP R* (%)	*CP R* (%)	*FP R* (%)	*RP R* (%)	*SP R* (%)
USA	86	1 (52)	1 (50)	1 (62)	1 (47)	1 (45)	1 (57)
UK	20	2 (12)	2 (11)	4 (17)	2 (10)	2 (11)	3 (8.7)
China	16	3 (9.8)	4 (5.9)	2 (28)	4 (6.7)	4 (7.1)	N/A
Germany	16	3 (9.8)	3 (8.1)	4 (17)	3 (7.9)	3 (8.4)	N/A
France	12	5 (7.3)	5 (4.4)	3 (21)	5 (6.1)	5 (6.5)	2 (17)
Israel	9	6 (5.5)	5 (4.4)	7 (10)	6 (4.9)	6 (5.2)	4 (4.3)
Japan	7	7 (4.3)	9 (2.2)	6 (14)	9 (1.8)	9 (1.9)	N/A
Sweden	6	8 (3.7)	7 (3.0)	10 (6.9)	7 (3.0)	7 (3.2)	N/A
Switzerland	5	9 (3.0)	7 (3.0)	12 (3.4)	7 (3.0)	7 (3.2)	4 (4.3)
Finland	4	10 (2.4)	11 (1.5)	10 (6.9)	9 (1.8)	9 (1.9)	4 (4.3)
Australia	3	11 (1.8)	9 (2.2)	N/A	9 (1.8)	12 (1.3)	N/A
India	3	11 (1.8)	11 (1.5)	12 (3.4)	9 (1.8)	9 (1.9)	N/A
Netherlands	3	11 (1.8)	N/A	7 (10)	13 (1.2)	12 (1.3)	N/A
Russia	3	11 (1.8)	N/A	7 (10)	N/A	N/A	N/A
Belgium	1	15 (0.61)	N/A	12 (3.4)	N/A	N/A	N/A
Belarus	1	15 (0.61)	13 (0.74)	N/A	14 (0.61)	14 (0.65)	N/A
Canada	1	15 (0.61)	N/A	12 (3.4)	14 (0.61)	N/A	N/A
Italy	1	15 (0.61)	13 (0.74)	N/A	14 (0.61)	14 (0.65)	4 (4.3)
Spain	1	15 (0.61)	13 (0.74)	N/A	14 (0.61)	14 (0.65)	N/A
Turkey	1	15 (0.61)	N/A	12 (3.4)	N/A	N/A	N/A

TP: total top – cited articles; *IP*: single – country top – cited articles; *CP*: internationally collaborative top – cited articles; *FP*: first – author top – cited articles; *RP*: corresponding – author top – cited articles; *SP*: single – author top – cited articles; *R*: rank; N/A: not available.

3.5. Distribution of Countries

Of the 164 top – cited articles with author affiliations, published by 20 countries, 135 (82% of 164 articles) were single country articles and 29 (18%) were internationally collaborative articles. The countries were ranked according to the number of total top – articles published and provided in Table 5. Rank includes the total number of articles (*TP*), single country articles (*IP*), internationally collaborative articles (*CP*), first author articles (FP), corresponding author's articles (*RP*), single author articles (*SP*) (Ho and Kahn, 2014). The leading country was the USA with 86 articles, accounting for 52%, followed distantly by the UK with 20 articles, China with 16 articles and Germany with 16 articles, and France with 12 articles. The G7 countries (the United States, the UK, Canada, Germany, France, Italy, and Japan) had high productivity in top – cited articles, which included 132 (80% of 164 top – cited articles with affiliations). Domination by mainstream countries in publication is not surprising, as this pattern has been occurred in many related fields such as materials

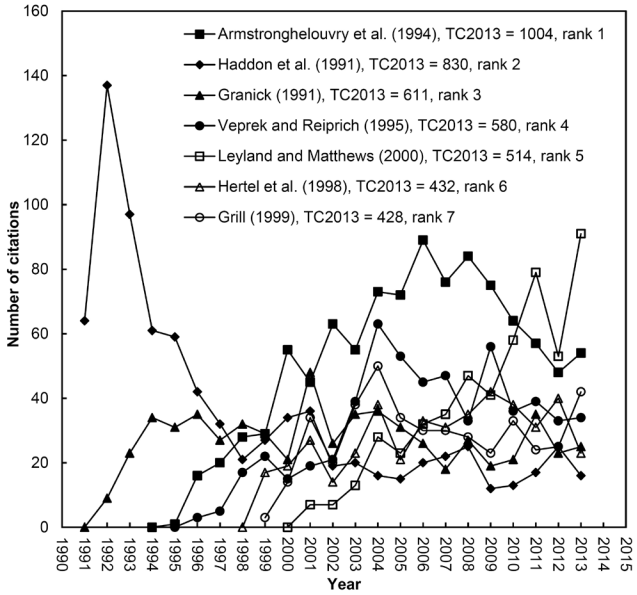

Figure 3

Citation life cycles of the top seven articles ($TC_{2013} \geq 400$)

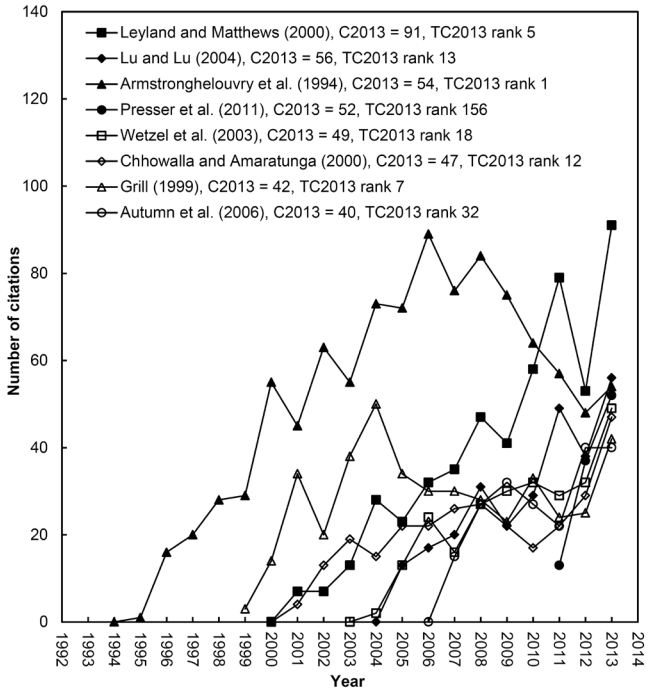

Figure 4

Citation life cycles of the top eight articles ($C_{2013} \geq 40$)

science [28], thermodynamic research [29], and nanotribology [47]. In terms of internationally collaborative articles, 62% were contributed by the USA; and as for non – collaborative independent articles, 57% were published by the USA. Moreover the USA ranked top for all the six indicators. There is a fluctuation in the ranks for all the six indicators among the top five contributing countries (the USA, the UK, China, Germany, and France). However China and Germany had no single author articles.

3.6. *Citation Life Cycles*

Total citations of articles were widely applied in most studies. Three kinds of citations: C_{2013}, TC_{2013}, and C_0 were employed to characterize the top – cited articles in tribology research. The articles with the highest TC_{2013} can be considered as the most popular articles in this research field. The total number of times an article was cited from its time of publication to the end of 2013 (TC_{2013}) was used [8, 35]. The advantage of this indicator is its invariance, not updating with time [7]. The citation lives of the top seven articles (TC_{2013} > 400) are shown in Fig. 3. Of seven articles, five were published before 2000. The three of the top seven articles in TC_{2013} were also found in the top seven in C_{2013} such as Leyland and Matthews [48], Armstronghelouvry et al. [49], and Grill [50]. Among the seven articles, the top article "On the significance of the H/E ratio in wear control: a nanocomposite coating approach to optimized tribological behavior" [48] by Leyland and Matthews published in 2000 showed a continual and sharp increase in citations in all years since its time of publication. This article is also top ranked one in C_{2013} = 91.

Earlier publications such as Haddon et al. [51], Granick [52], Veprek and Reiprich [53], and Hertel [54] had a long impact history, but much less impact in the recent years (e.g. C_{2013}), these four articles were published during 1990s. Top ranked article in TC_{2013} by Armstronghelouvry et al. [49] surveyed the contributions from the tribology, wear and physics literatures as well as the controls literature which are important for the understanding and compensation of friction in servo machines. A set of models and tools for friction compensation was provided which is useful to both research scientists and application engineers. In which servo – control techniques was also demonstrated.

Since TC_{2013} is an accumulative number that may reach a large value as long as the time span is long enough, it is necessary to study the citations of an article cited within every single year (2013) to interpret the research focus transfer in recent years. The citation life curves of the top eight articles ($C_{2013} \geq 40$) are shown in Fig. 4. All these articles were published in 2000s except one article which had published in 1994. One earlier article "A survey of models, analysis tools and compensation methods for the control of machines with friction" by Armstronghelouvry et al. [49] had a long impact history since its publication. Top ranked article in the recent year (C_{2013}) by Leyland and Matthews [48] discussed the concept of nanocomposite coatings with high hardness and low elastic modulus, which can exhibit improved toughness, and are therefore better suited for optimizing the wear resistance of "real" industrial substrate materials.

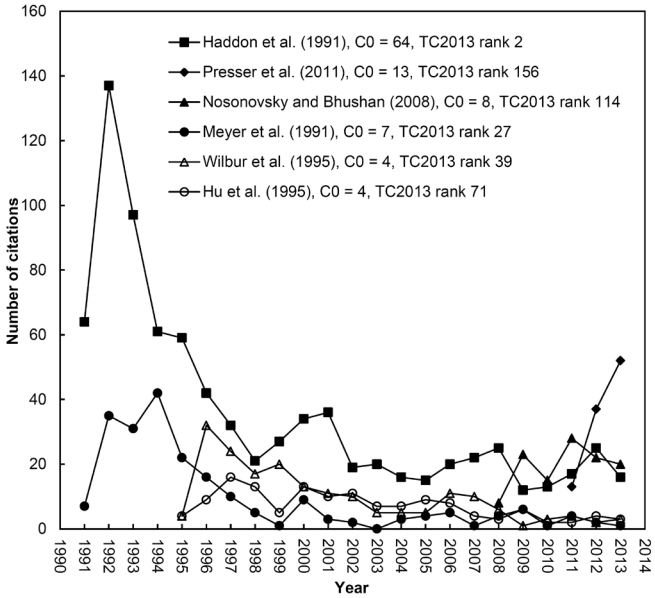

Figure 5

Citation life cycles of the top six articles ($C_0 \geq 4$)

Articles with higher citations in the publication year (C_0) were likely to cite in recent years. Figure 5 shows the citation life of the top six most cited articles in their publication year ($C_0 \geq 4$). Among them, two articles were published in 1991 and 1995 respectively. Each one article was published in 2008 and 2011. Top – cited article in its publication year (C_0) "Conducting films of C_{60} and C_{70} by alkali – metal doping" by Haddon et al. [51] was also the second top – cited article in TC2013. Haddon et al. [51] reported the preparation of alkali – metal – doped films of C_{60} and C_{70} which have electrical conductivities at room temperature that are comparable to those attained by n – type doped polyacetylene. All the articles had increasing trend of citations after their publications then showed decreasing trends in the following years.

3.7. *Distribution of words in titles, author keywords, and KeyWords Plus*

In last decade, Ho and co – workers presented that the distribution of words in article titles, author keywords, and *KeyWords Plus* to evaluate trends in research topics [37, 55, 56]. Detection of certain words in the abstracts of papers has also been used as information to determine research trends [57]. The words in titles and author keywords supply reasonable details of the article subjects and include the information which author would like to express to their readers [58]. Only 97 top – cited articles had author keyword information in Web of Science. Author keywords that appeared at least three times in top – cited articles are listed in Table 6. The most frequently used author keywords are "friction", "wear", and "tribology". We also analyzed all the single words in the titles of top – cited articles in

Table 6

Distribution of author keywords

Author keyword	*TP*	Rank	%
Friction	25	1	26
Wear	22	2	23
Tribology	20	3	21
Diamond – like carbon	11	4	11
Adhesion	5	5	5.2
Lubrication	5	5	5.2
Contact mechanics	4	7	4.1
Atomic force microscopy	3	8	3.1
Biocompatibility	3	8	3.1
Coating	3	8	3.1
Deposition	3	8	3.1
DLC	3	8	3.1
Lubricant	3	8	3.1
Mechanical properties	3	8	3.1
Mems	3	8	3.1
Nanocomposite	3	8	3.1
Piston rings	3	8	3.1
Polymers	3	8	3.1
Silicon nitride	3	8	3.1
Stiction	3	8	3.1
Surface texturing	3	8	3.1
Tribochemistry	3	8	3.1
Wear resistance	3	8	3.1

TP: total number of articles

tribology research. Some prepositions for example "of" and "in", were discarded, as they are meaningless for further study [57]. The most used single words in titles were "tribological" which appeared in 35 articles followed by "wear" (29), "coatings" (27), "carbon" (25), "properties" (25), and "friction" (24). Some words such as carbon, coatings, DLC, ceramic, materials, and composites were frequently used titles and it shows that this research area is based on the materials. "Tribological" is the most frequently used word both in titles and abstracts as it was used as searching keyword to retrieve the bibliographic records related

to tribology research. All together 146 top – cited articles had *KeyWords Plus* information in Web of Science. Analysis results shows that the keywords "behavior", "films", "friction", "wear", "thin – films", and "surface" are highly visible. Distribution of words show that some keywords were appeared among the top ranks in all the forms of words analysis such as "tribology", "tribological", "wear", "friction", "diamond – like carbon", "carbon or DLC", "coatings", "materials", and "composite".

4. Conclusion

In total, 165 top – cited articles were published between 1971 and 2011 in the field of tribology in SCI – EXPANDED. Most of the top – cited articles were published in the 1990s while none was published during the years 1972 – 84. Authorship with a small group was found in the top – cited articles. Most articles published in six core journals, such as *Surface & Coatings Technology, Wear, Tribology International, Nature, Tribology Letters, and Diamond and Related Materials*. There was no focus on any special subject categories but scattered across to materials science, mechanical engineering, and applied physics fields. From the distribution of *Y* – index results, A.A. Voevodin and B. Bhushan had the most publication potential. K. Friedrich and M. Grischke published more first authored articles while S. Jacobson published only corresponding authored articles. Non – academic institutions such as IBM Corporation of the USA and Argonne National Laboratory of the USA were most active on top – cited articles in tribology. The USA published more than half of top – articles followed distantly by the UK. Citation life cycles (an article's publication year, in the most recent recorded year, and total citations from publication to the end of 2013) showed different rankings of top – cited articles. Results of keywords analysis show that this research field is bounded to materials especially to carbon.

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