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INVITED ARTICLE

Highly Cited Articles of Corrosion Research in Science Citation Index Expanded

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This study aimed to identify and analyze the characteristics of the highly cited articles published in corrosion related fields in the Science Citation Index Expanded from 1900 to 2012. Articles that have been cited more than 100 times since publication to 2012 ($TC_{2012} \geq 100$) were assessed. Analyzed aspects concerned the publication patterns of decades, journals, categories, institution, country and citation life cycles. Citations in the first two years after publication (TC_2), in 2012 (C_{2012}) and since publication to 2012 (TC_{2012}) and citations per year of each article (TCPY) were innovatively used to characterize the citation patterns. Most of the articles were published in 1990s and 2000s. *Corrosion Science*, *Journal of the Electrochemical Society*, *Corrosion* and *Electrochimica Acta* were the core journals. Corrosion research is mainly published in technology and physical sciences research areas and multidisciplinary materials science, metallurgy and metallurgical engineering, electrochemistry and coatings and films materials categories. Seven industrialized countries: the USA, Germany, UK, France, Japan, Canada and Italy played an important role. In addition, the relation of citations with time and impact factor has been revealed.

Keywords: Corrosion, SCI-Expanded, Bibliometric, Top-Cited Articles, Citation, Web of Science.

INTRODUCTION

Two chapters entitled "of the mechanical origin of corrosiveness" and "of the mechanical origin of corrodibility" by Robert Boyle in 1675 were considered the origin of corrosion research [1]. In the beginning of 19th century, the whole subject of corrosion was observed an electrochemical phenomenon [2]. The corrosion of ammonium nitrite [3], diazo solutions [4], brasses [5], iron and steel [6] were paid attention. The research on the corrosion of brasses in 1907 received an award granted by the American Electrochemical Society [5]. The Technical Committee on Corrosion, the forerunner of the Corrosion Division of electrochemical society, was formed in 1921 [7]. In 1930s, important symposia "inhibitors, corrosion and pH, corrosion of alloys and influence of cathodic reactions on corrosion" were presented [7]. Pourbaix [8] introduced thermodynamics in corrosion studies and potential-pH diagrams, now known as Pourbaix Diagram [9]. The emergence of new electrochemical and non-electrochemical techniques for the study of corrosion reactions and corrosion products greatly accelerated during the 1970s and has continued to the present day [10]. Some outstanding scholars *e.g.*, Tammann, Evans, Wagner, Pourbaix, Ulig, Fontana and Hackerman greatly advanced corrosion research [1].

A bibliometrics method was previously employed to evaluate scientific production of corrosion papers from 1992 to 2007, giving the panorama of global corrosion research [11]. This study focused on the highly cited corrosion-related articles for more than one hundred years of 1900-2012. Highly cited articles [12], also called most frequently cited articles [13], most cited papers [14], citation classics [15] and top cited papers [16], are intellectual tours and force with quite minimal technology [17]. The bibliometrics analyses of highly cited articles could help reveal the recognition of scientific advancement and to give a historic perspective on the scientific progress [18,19]. The research of highly cited articles could be dated back to a series of studies in 1970s by Garfield [12,13,20]. Most of the early research of highly cited articles just identify and list the basic information with few discussion, such as authors, title and published year of them [21,22]. Recently, scientists employ multi-dimensional indicators and methods to provide more comprehensive characteristics of highly cited articles. Total citations of a paper has been widely applied to be a bibliometric indicator [23,24], while a newly developed indicator, total number of citations of an article from its publication to recent year, was presented [25,26] to overcome the limitations of the former [27]. Indicators such as numbers of authors cited, numbers of institutions cited, numbers of countries

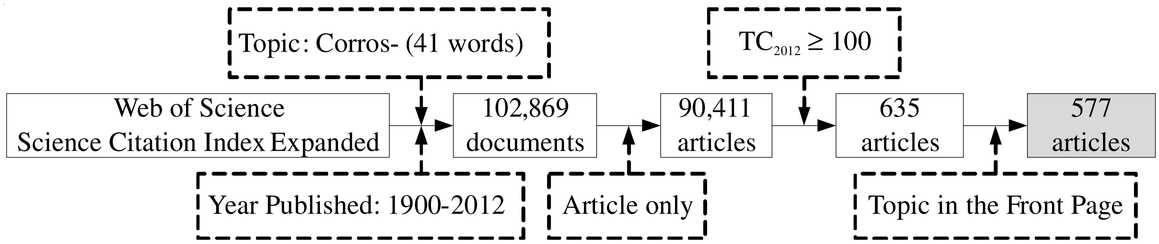

Fig. 1. Schematic for searching the highly cited articles

cited, numbers of subject areas cited, citations per year and total number of citations of a paper to date have been applied to the high-impact papers on the subject of water resources [25] and adsorption [27]. The distribution of publication output, categories, contributing institutions, countries [27], collaboration [28,29] and policy implication [30] attach much attention. The citations of an article in a year differed with time [31] and the citation life cycles of highly cited papers were revealed to provide more valid information for pioneers [27]. In addition, the frequency of words in title and author keywords in successive sub-periods have been quantitatively analyzed to figure out focuses and trends of China's independent highly cited research [32].

This study carried out in-depth analysis of the highly cited articles associated with corrosion in Science Citation Index Expanded (SCI-EXPANDED) from 1900 to 2012 through some improved bibliometric methods. The characteristics of publication year, journals, Web of Science categories, research areas, authorship, institutions, countries, citation life cycles and the effect of time and impact factor on citations were examined.

EXPERIMENTAL

Data collection: The documents was based on the SCI-EXPANDED database of Web of Science from Thomson Reuters (updated on 05 June 2013). The schematic for searching highly cited articles is shown in Fig. 1 [27]. Forty-one related keywords including corros, corrosa, corrosao, corrosian, corrosible, corrosif, corrosifs, corrosin, corrosing, corrosiological, corrosiologists, corrosiology, corrosiometry, corrosiometry, corrosion, corrosional, corrosionanatomical, corrosione, corrosione, corrosione, corrosioneering, corrosioni, corrosionist, corrosionist, corrosionists, corrosionless, corrosionresistant, corrosions, corrosions, corrosiva, corrosive, corrosively, corrosiveness, corrosivite, corrosivity, corrosivus, corrosometric, corrosometry, corrospanding, corrossion and corrosus were searched in "Topic" field from 1900 to 2012. Altogether 102,869 documents were found. Documents with "corrosive sublimat≥ in "Topic" field were not considered to be corrosion-related articles. Secondly, articles (90,411) were abstracted as the only considered document type. Other document types including meeting abstract, note, review, editorial material, letter, news item, discussion, book review, correction, reprint, correction addition, abstract of published item, biographical item, software review, item about an individual and bibliography were all excluded. Thirdly, $TC_{2012} \geq 100$ was used as a filter to extract 635 articles as the highly cited articles TC_{2012} which could ensure repeatability [27], is the total citation since articles were published to the end of 2012 [25]. The final filter was the front page [27], which meant only 577 articles with the searching keywords in their front pages including article title, abstract and author keywords were searched out.

Analytic structure and indicators: The analytic structure of characteristics of highly cited articles is presented in Fig. 2. The characteristics were divided in to five parts for in-depth analyses by bibliometric indicators. Classify was carried out to mend some database defects in terms of affiliation. Articles originating from England, Scotland, Northern Ireland and Wales were reclassified as being from the United Kingdom [33]. Federal Republic of Germany and Germany were reclassified as being from Germany [34]. Articles from Hong Kong before 1997 were included in China [35]. The contributions from institutes' and countries/territories' were identified by the appearance of at least one author in the publications. Collaboration type was determined by the affiliations of the authors. Five types of articles were introduced for the evaluation of countries and institutes. (1) The term "single country article" was assigned if the researchers' affiliations were from the same country. The term "single institute article" was assigned if the researchers' affiliations were from the same institute. (2) The term "internationally collaborative article" was designated to those articles that were coauthored by researchers from multiple countries [33]. The term "inter-institutionally collaborative article" was assigned if authors were from different institutes. (3) The term "first author article" was assigned if the first author was from the country/territory or institute for analysis. (4) The term "corresponding author article" was assigned if the corresponding author was from the country/territory or institute for analysis. (5) The term "single author article" was assigned if the article was published by only one author. TP, IP, CP, FP,

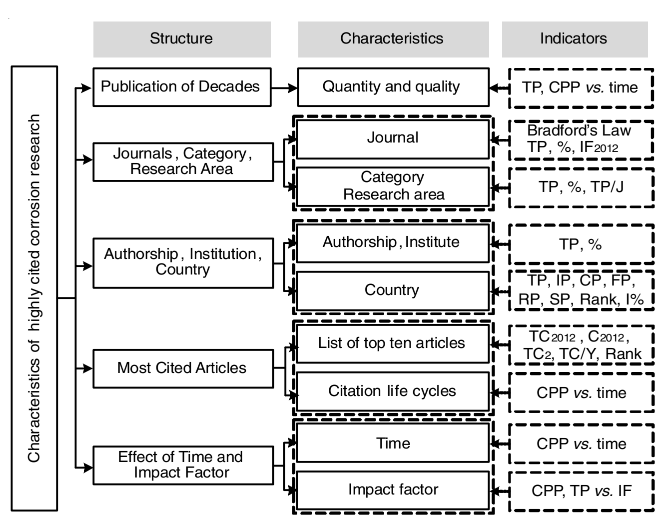

Fig. 2. Analytic structure of characteristics of highly cited articles

RP and SP are the number of total articles, "single country articles" or "single institute articles", "internationally collaborative articles" or "inter-institutionally collaborative articles", "first author articles", "corresponding author articles" and "single author article" for a country/territory or a institute, respectively. The calculation for all results was processed in the Microsoft Excel 2007.

RESULTS AND DISCUSSION

Publications characteristics by decades: Altogether 577 highly cite articles, 0.64 % of 90,411 articles, were published in the past 73 years between 1938 and 2010. Fig. 3 illustrates the quantity and citations per publication (CPP) of these 577 articles over nine decades. The most two productive decades were 1990s with 254 articles (44 %) and 2000s with 212 articles (37 %). The publication output of 1910s-1970s and 2010s had 112 articles, only taking up 19 %. Only one article was published in 1930s and 2010s, while no highly cited articles emerged in the latest two years: 2011 and 2012. Few highly cited articles in early and recent years could be due to the increasing change of being forgotten and less time for the accumulation of citations [21]. Another possible reason might be that the number of journals in SCI database increased from 4,963 in 1997 to 8,411 in 2012. The bigger scientific size of database provide more chances of being cited. Similar phenomenon could also be found in the other research fields of adsorption [27], chemical engineering [36] and social science [37].

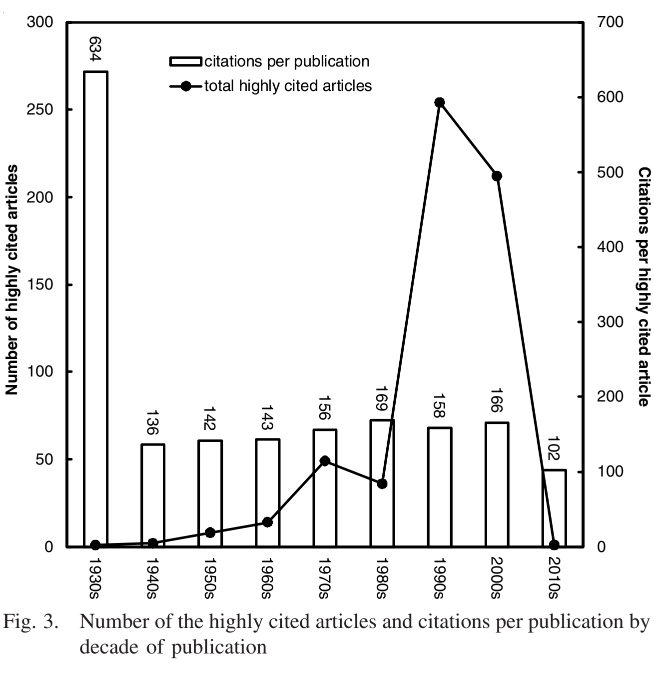

Fig. 3. Number of the highly cited articles and citations per publication by decade of publication

TC_{2012} ranged from 100 to 2,773 citations, with 162 citations per publication (CPP) on average. The high CPP of 634 in 1930s can be attributed its small size of only one article and its great citations [27]. This article entitled "the analysis of corrosion procedures through the interaction of electrochemical partial procedures and on the potential difference of mixed electrodes" was published by Wagner and Traud in 1938 [38] with a TC_{2012} of 634. This was not only the earliest highly cited corrosion article in SCI-Expanded, but also the only one article in non-English language, German. Wagner received the first Palladium Medal Address in recognition of accomplishments upon the understanding of corrosion in 1951 [7]. The latest highly cited article was published in 2010, "Research on an Mg-Zn alloy as a degradable biomaterial" [39] by Chinese team in Shanghai Jiao Tong University, with a TC_{2012} = 102 ranked in 538th. Except 1930s and 2010s, the CPPs other seven decades 1940s-2000s fluctuated in a small range of 136-169 citations.

Journals, Web of Science categories and research areas: Distribution of the highly cited articles concerned journals and subject categories [27]. The highly cited corrosion articles were published by 176 journals issued by nine countries including the USA (71 journals; CPP = 165), the UK (49; 171), Netherlands (28; 153), Switzerland (14; 131), France (3; 127), Germany (3; 115), Japan (3; 138), Canada (2; 116) and Denmark (1; 119), except two journals without publisher information in Web of Science. Of these 176 journals, 111 (63 %) journals contained only one article; 31 (18 %) journals contained two articles; eight (4.6 %) journals contained three articles and 26 (15 %) journals contained more than three articles. According to Bradford's Law of Scattering [40], the journals can be classified into three "zones", each producing about one-third of all articles. The journals in descending order in terms of their published articles were sorted. Zone 1 represents the most productive four journals (2.3 %) with one-third of the total articles. Zone 2 represents the next most productive 25 (14 %) journals with one-third of total articles and Zone 3 represents the least productive 147 (84 %) journals with one-third of total articles. The number of journals in these three zones was approximately $1:n:n^2$::1:6.3:37, followed Bradford's law. Four Bradford's core journals were *Corrosion Science* (IF_{2012} = 3.615), *Journal of the Electrochemical Society* (IF_{2012} = 2.588), *Corrosion* (IF_{2012} = 1.772) and *Electrochimica Acta* (IF_{2012} = 3.777).

Table-1 shows the top ten productive journals, accounting for 52 % of all highly cited articles. *Corrosion Science* was the most productive journal with 85 articles (15 %). The percentage of the top productive journal was high, which indicates that the corrosion research focused on specific topics. The journals with the highest impact factor were *New England Journal of Medicine* (IF_{2012} = 51.658) with one medical related article entitled "A controlled trial of corticosteroids in children with corrosive injury of the esophagus" [41], followed by *Nature* with eight articles (IF_{2012} = 38.597) and *Nature Materials* with one articles (IF_{2012} = 35.749). The most-cited publications did not always appear in the highest impact journals [42]. Articles with $TC_{2012} \geq 100$ could be also found in journals with low impact factors such as *Materials Evaluation* with IF_{2012} = 0.269, *Insight* with IF_{2012} = 0.450, *Radiation Effects and Defects in Solids* with IF_{2012} = 0.502 and *Journal of Laser Applications* with IF_{2012} = 0.574. In addition, the ninth *Journal of Biomedical Materials Research* was not listed in JCR after 2004.

Based on the Web of Science categories in 2012, the highly cited articles were distributed in 67 science subject categories. Multidisciplinary materials science (218; 38 % of all articles) was the most common category included 232 journals; followed by the categories of metallurgy and metallurgical engineering

TABLE-1
CHARACTERISTICS OF TOP TEN JOURNALS WITH THE HIGHLY CITED ARTICLES

Journal	TP (%)	IF_{2012}	PC	Web of Science subject category (Position)
Corrosion Science	85 (15)	3.615	UK	Multidisciplinary Materials Science (34/232); Metallurgy And Metallurgical Engineering (2/75)
Journal of the Electrochemical Society	55 (10)	2.588	USA	Electrochemistry (13/27); Coatings and Films Materials Science (1/18)
Corrosion	33 (5.7)	1.772	USA	Multidisciplinary Materials Science (100/232); Metallurgy and Metallurgical Engineering (11/75)
Electrochimica Acta	29 (5.0)	3.777	UK	Electrochemistry (7/27)
Surface & Coatings Technology	25 (4.3)	1.941	Switzerland	Coatings and Films Materials Science (5/18); Applied Physics (43/125)
Biomaterials	19 (3.3)	7.604	UK	Biomedical Engineering (2/72); Biomaterials Materials Science (1/25)
Environmental Science & Technology	16 (2.8)	5.257	USA	Environmental Engineering (3/45); Environmental Sciences (8/205)
Journal of Power Sources	13 (2.3)	4.675	Netherlands	Electrochemistry (2/27); Energy and Fuels (9/81)
Journal of Biomedical Materials Research*	12 (2.1)	2.397	USA	Biomedical Engineering (4/42); Biomaterials Materials Science (2/15)
Materials Science and Engineering A-Structural Materials Properties Microstructure and Processing	9 (1.6)	2.108	Switzerland	Multidisciplinary Materials Science (61/232); Nanoscience and Nanotechnology (33/66)

TP: Total number of highly cited articles; IF_{2012}: impact factor in 2012; PC: issued country; Rank: impact factor rank in a category; *: impact factor and position in JCR of 2003.

(152; 26 %) with 75 journals, electrochemistry (111; 19 %) with 27 journals and coatings and films materials science (94; 16 %) with 18 journals. These four categories contributed 65 % of all highly cited articles. Domination of multidisciplinary materials science was not surprising, since there were a large number of journals (232) in this category. A new indicator, number of highly cited articles per journal in a category (TP/J), was employed to compare the characteristics of different categories. Category of coatings and films materials science including 18 journals had the highest TP/J of 5.2, followed by electrochemistry (27 journals, TP/J = 4.1) metallurgy and metallurgical engineering (75 journals, TP/J = 2.0) and biomaterials materials science (25 journals, TP/J = 1.4). The number of journals in one category have a positive relation with the TP/J.

There are five research areas including 151 research domains in Web of Science. Highly cited corrosion articles were published in 42 research domains. Materials science, metallurgy and metallurgical engineering and electrochemistry contributed more than 100 articles. The results of categories and research domains were very similar. The research area technology had 440 articles, taking 76 %, followed by physical sciences (253 articles; 44 %) and life sciences and biomedicine (56 articles; 10 %).

Authorship, Institution and Country: Each author in one publication made contributions to the research work [43]. In the research of highly cited articles, scientists are the crucial factors in determining the distribution of institutes and countries [27]. The average number of authors in corrosion research was 3.4, with 12 as the largest number of authors for one highly cited article. Before 1972, highly cited articles were all contributed by one to three authors. The average number of authors per article increased from 2.0 in 1930s and 1940s to 1.8 in 1950s and 1960s, up to 4.1 in 2000s. Of the 577 highly cited articles, 76 (13 %) were written by single author, 137 (24 %) by two authors, 136 (24 %) by three authors, 90 (16 %) by four authors, 65 (11 %) by five authors and 73 (13 %) by more than five authors. High percentage of single authored highly cited articles was not usual, comparing with all related publications in a research field such as biomedical and life sciences [44], ocean circulation [45] and biosorption technology in water treatment research [46]. Increase in the number of authors per article indicates that multiple-authorship is becoming the norm [47]. It is noticed that gift authorship was prevalent in recent survey [48]. This prevalent unethical authorship led to obfuscation of authorship credit within by-lines [49]. Concerted efforts by institutions, authors and journals are needed to put an end to this fraudulent and unethical practice [50].

Publication performance of institutes and countries have been investigated by number of total, independent and collaborative publications [51]. Single author articles published by institutions and countries were also discussed. Total 40 highly cited corrosion articles without any author affiliation information in the Web of Science were excluded, including 16 in the 1970s, 13 in the 1960s, eight in the 1950s and one in each of 1938, 1940 and 1990, respectively. Altogether, 537 articles originated from 516 institutions in 44 countries.

Eighty-five articles (16 %) were international collaboration, while the other 452 articles (86 %) were independent articles, contributed by only one country. The collaboration rate (16 %) was less than 20 % in the field chemical engineering sorption technology for water treatment [52], similar with 17 % of top cited reviews with more than 1,000 citations [42] and greater than 14 % of in adsorption research [27]. The citations per article for independent articles (166) was greater than that of internationally-collaborative articles (161). Although some previous studies identified that collaboration could increase the average impact of articles [53], this phenomenon is not conformed to the pattern here. The top 10 countries with the information of total articles, independent articles, internationally collaborative articles, first author articles, corresponding author articles, single author articles and number of institutions for each country are listed in Table-2. The USA dominated the

TABLE-2
TOP TEN COUNTRIES OF HIGHLY CITED ARTICLES

Country	TP	TPR (%)	IPR (%)	CPR (%)	FAR (%)	RPR (%)	SPR (%)	I %
USA	215	1 (40)	1 (39)	1 (47)	1 (36)	1 (35)	1 (44)	81
Germany	64	2 (12)	3 (9.1)	2 (27)	3 (9.1)	2 (10)	3 (7.4)	64
UK	59	3 (11)	2 (10)	4 (14)	2 (9.5)	3 (8.9)	3 (8.8)	80
France	41	4 (7.6)	6 (4.9)	3 (22)	4 (6.0)	4 (6.0)	11 (1.5)	54
China	33	5 (6.1)	5 (5.1)	6 (12)	6 (4.7)	6 (5.2)	11 (1.5)	70
Japan	30	6 (5.6)	4 (6.2)	14 (2.4)	5 (5.6)	5 (5.4)	2 (10)	93
Canada	26	7 (4.8)	7 (3.1)	4 (14)	7 (3.9)	7 (4.3)	7 (2.9)	54
Australia	18	8 (3.4)	8 (2.4)	8 (8.2)	8 (3.2)	8 (3.3)	7 (2.9)	61
Switzerland	14	9 (2.6)	9 (2.2)	10 (4.7)	9 (2.2)	9 (2.5)	7 (2.9)	71
Italy	13	10 (2.4)	10 (2.0)	10 (4.7)	10 (1.9)	10 (2.1)	7 (2.9)	69

TP: total number of highly cited articles; TPR (%), IPR (%), CPR (%), FPR (%), RPR (%) and SPR (%): the rank and percentage of total articles, single country articles, international collaborative articles, first author articles, corresponding author articles and single author articles in their total articles; I %: the percentage of single country articles in total articles for each country.

field, accounting for 40 % of all articles, followed distantly by other countries. Though in terms of total scientific production the USA has been exceeded by China since 2006 [32], the phenomenon that the USA still held its superiority is normal by studying highly cited articles. The percentages of the USA in some previous studies were 72 % of wetland research [54], 66 % in environmental sciences and 49 % in chemical engineering [36]. Except the USA, the other six industrialized countries: Germany, the UK, France, Japan, Canada and Italy, were all listed in the top 10 countries. These 7 countries (G7) took up 77 % in the total articles. Only one developing country in the top ten countries, China, ranked 5th in the total articles, but 11th in the singly author articles. All the top 10 countries had more independent articles than internationally collaborative articles (I % > 50 %). In particular, an overwhelming majority of Japan's articles was contributed independently (I % = 93 %).

In total 330 articles (61 %) from independent institutions and 207 articles (39 %) from inter-institutional collaboration. The inter-institutional collaboration rate of highly cited articles was observed to be smaller than numerous fields with all related articles [55,56], but was greater than the highly cited articles of certain medical fields [19,57]. Top three universities were Tohoku University of Japan with 12 articles, Chinese Academy of Sciences of China with 11 articles and Ecole Nationale Supérieure de Chimie de Lille (ENSCL) of France with 10 articles. Tohoku University published the most independent institution articles, having a high percentage of 92 %, indicating a strong independent ability of scientific research. Chinese Academy of Sciences and ENSCL collaborated with other institutions for eight publications, respectively. Especially, ENSCL did not publish any single author articles. It is noticed that the Chinese Academy of Sciences has many branches in many cities and dividing the articles among the branches would have given different rankings [58].

Citation life cycles of highly cited articles: Citation analysis is a common method for quantifying scholarly contribution or research visibility [59]. Highly cited papers are of particular importance, since a high citation count is an indication of high impact or visibility on the research community [60]. Citations of topmost highly cited publications changed over time [61]. Except the total citations TC_{2012}, the total number of citations of an article in 2012 (C_{2012}) [36] and the total number of citations of an article in its publication year (C_0) were recently developed to offer more detail information about the impact of a publication [42,61]. It is reported that one quarter highly cited articles had no citations in the publication year ($C_0 = 0$) [63]. Fifty-eight percent of the articles in the top 100 by TC_{2012} were not ranked in top 100 by C_0 and total 369 articles (64 % of 577 highly cited articles) had no citation in the publication year ($C_0 = 0$) in the corrosion research. This indicated that C_0 have a weak correlation with the whole influence of highly cited articles. Thus, a new indicator TC_2, the sum of C_0, C_1 (the number of citations in the first year after publication), C_2 (the number of citations in the second year after publication) was introduced to characterize the initial influence of highly cited articles. Furthermore, investigation based on citations per year (TCPY) was presented in this study. It took the time for citation accumulation into consideration, providing deeper insights into the citations characteristics of highly cited articles. In total, 388 articles (67 % of 577 highly cited) was cited no more than once in a month on average (0 < TCPY ≤ 12), 142 articles (25 %) had 12 < TCPY ≤ 24. Twelve articles (2.1 %) had TCPY ≥ 50 citations with the highest TCPY of 231 which was the only one three digitals of TCPY.

The correlation coefficients (Pearson's coefficients) of the traditional indicator TC_{2012} and three newly developed indicators including C_{2012}, TC_2 and TCPY, were 0.73, 0.43 and 0.77, respectively. It is noticeable that TC_{2012} have a better correlation with C_{2012} and TCPY than TC_2. Table-3 exhibits the ten most cited articles cited for more than 450 times (TC_{2012} > 450). Out of these ten articles, three were published before the 1990s, four in 1990s and three in 2000s. Most of the top ten articles differed by each indicator. That means the highly cited articles would not always have high impact or visibility in research society after their publications. It has also been reported that most frequently cited articles in *American Journal of Roentgenology* have changed their rankings [62]. Only one article was listed in top five by four indicators and meanwhile won the first position in these four lists. This article was published by Inoue in 2000 [63] with the highest TC_{2012} (2,773), C_{2012} (265), TC_2 (170) and TCPY (231). The first article was "the analysis of corrosion procedures through the interaction of electrochemical partial procedures and on the potential difference of mixed electrodes" in 1938 and the latest one was "factsage thermochemical software and databases" in 2002. Both articles were published in *Nature*.

TABLE-3
TEN MOST FREQUENTLY CITED CORROSION-RELATED ARTICLES (TC_{2012} > 450)

Rank (TC_{2012})	Rank (C_{2012})	Rank (TC_2)	Rank (C/Y)	Article title	Journal	Year	Ref.
1 (2,773)	1 (265)	1 (170)	1 (231)	Stabilization of metallic supercooled liquid and bulk amorphous alloys	*Acta Materialia*	2000	[63]
2 (1,333)	6 (78)	219 (11)	3 (63)	The exchange-spring magnet: A new material principle for permanent magnets	*IEEE Transactions on Magnetics*	1991	[66]
3 (688)	14 (61)	219 (11)	29 (33)	Sonochemical synthesis of amorphous iron	*Nature*	1991	[78]
4 (671)	2 (151)	61 (28)	5 (61)	Evolution of nanoporosity in dealloying	*Nature*	2001	[71]
5 (665)	25 (49)	59 (29)	21 (37)	Reductive dehalogenation of chlorinated methanes by iron metal	*Environmental Science & Technology*	1994	[67]
6 (634)	361 (8)	429 (4)	328 (8.6)	The analysis of corrosion procedures through the interaction of electrochemical partial procedures and on the potential difference of mixed electrodes	*Zeitschrift fur Elektrochemie und Angewandte Physikalische Chemie*	1938	[38]
7 (632)	95 (25)	561 (0)	117 (16)	Interface morphology development during stress-corrosion cracking: Part I. *via* surface diffusion	*Metallurgical Transactions*	1972	[68]
8 (540)	18 (56)	36 (35)	8 (54)	FactSage thermochemical software and databases	*Calphad*	2002	[79]
9 (500)	37 (39)	219 (11)	35 (28)	Waste-water minimization	*Chemical Engineering Science*	1994	[80]
10 (465)	285 (11)	316 (7)	211 (11)	Stress corrosion and static fatigue of glass	*Journal of the American Ceramic Society*	1970	[81]

TC_{2012}: number of citations till 2012; C_{2012}: number of citations in 2012; TC_2: number of citations the number of citations in the first two years after publications; TCPY: total citations per year.

The relation between citations of a paper and time has long been investigated [64]. Citation life of publications also provided the impact history of publications [42,64]. Highly cited articles were clustered to be the delayed rise, slow decline group and early rise, rapid decline group [65]. The citation lives of the top cited wetland articles [54] and the top cited adsorption related articles [27] were also studied in recent years. The citation lives of the top five articles (TC_{2012} > 600) are shown in Fig. 4. Three articles were published in 1990s, two in 2000s and one in 1938 and 1972, respectively. Different citations lives could be found. The first position "Inoue [63]" rose sharply to a peak of 393 articles per year in 2007 and then dropped to 265 in 2012. "Kneller and Hawig [66]", "Matheson and Tratnyek [67]" and "Asaro and Tiller [68]" increased and quickly reached a plateau around 2000. Another typical citation pattern could also be found for "Wagner and Traud [38]", with small but continuous influence for 75 years. The main reason why old articles are still highly cited is that they are relevant and valuable even today [69]. The most frequently cited article entitled "stabilization of metallic super-cooled liquid and bulk amorphous alloys" [63] in *Acta Materialia* (IF_{2012} = 3.941) was published by only single author *i.e.*, A. Inoue at Institute for Materials Research, Tohoku University of Japan. The work of Inoue opened the door to the design of new families of bulk metallic glasses and attention was once again focused on the investigation on bulk metallic glasses [63,70]. Inoue received Japan Academy Prize in 2002, James C. McGroddy Prize for New Materials in 2008 and *Acta Materialia* Gold medal in 2010. Citations of the article "Evolution of nanoporosity in dealloying" by Erlebacher *et al.* [71] rocketed after its publication. A continuum model was presented and it is suitable for sensor applications, particularly in a biomaterials context. Based on the citation trend, the article by Erlebacher *et al.* [71] might probably be a new focus topic in corrosion research field.

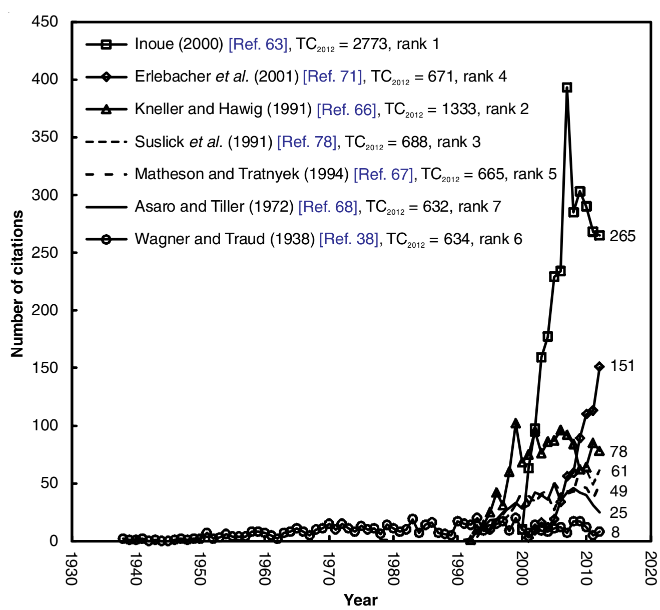

Fig. 4. Life of the top five most frequently cited highly citedarticles (TC_{2012} > 600)

Effect of time and impact factor on citation analysis: Citations of one's work is a better measure of the impact of an individual's works than how many papers a person has authored [72]. The citations per publication (CPP) for all the 577 highly cited articles in the number of years after publication is displayed in Fig. 5. After publication year, citations per publication of articles sharply increased to a peak in 5th year, stayed stable in the next five years and then decreased around one decade. The peak year of citations per highly cited article was found to be longer than other research disciplines of all related articles where the peak could be shifted to 2nd year [33,73], 5th year [44] and 6th year [74]. In clinical physiology

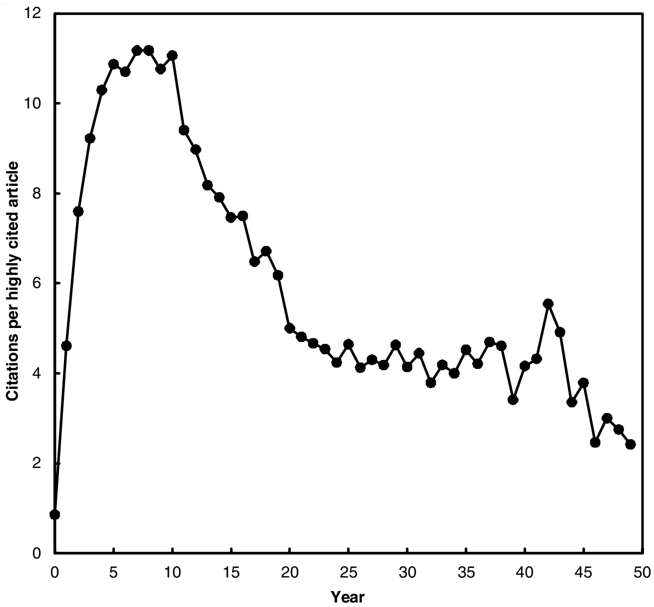

Fig. 5. Variation of citations per article with article life

and nuclear medicine research fields, citations per year reached a maximum or plateau 3-7 years after publication (count from year one) and the yearly citation rates were found to be the same order as the average journal impact factor [75].

Citations per publication (CPP) and number of highly cited articles in different impact factors (IF_{2012}) of journal from 2012 JCR displayed in Fig. 6. The impact factor is defined by JCR as the number of citations of all papers published in the previous 2 years, divided by the total number of papers published in those years. The IF_{2012} ranged from 0.269 of *Materials Evaluation* to 51.658 of *New England Journal of Medicine*. Most articles were published in the journals with $1 \leq IF_{2012} < 4$, accounting for 70 % of the total articles. Except $20 \leq IF_{2012} < 50$ with CPP = 257, the other CPPs of different IF_{2012} ranges were closed to each other. It seems that the citations of the highly cited articles did not have an obvious relation with impact factor. Throughout

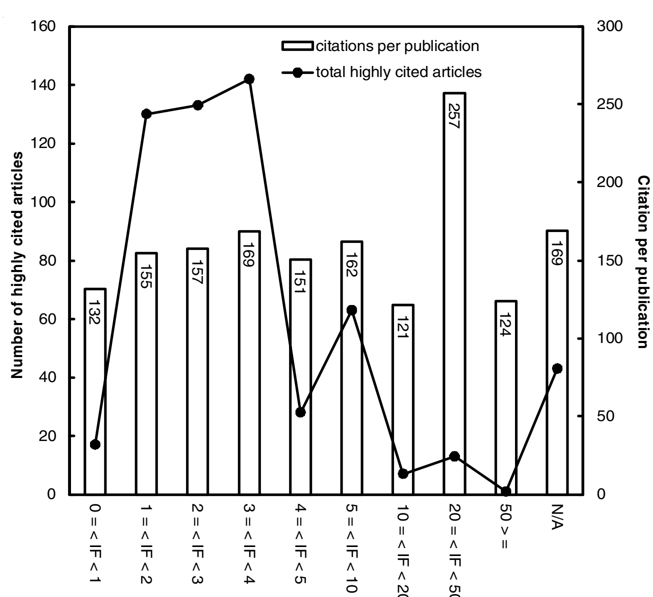

Fig. 6. Citations per publication and number of highly cited articles by different impact factors

most of the 20th century, papers' citation rates were increasingly linked to their respective journals' impact factors, while since 1990, the relation between IFs and paper citations has been weakening [76]. In most of the cases of hard sciences and social sciences journals, journal impact factors and their yearly variations do not display a strong correlation with citedness [77].

Conclusions

The global highly cited corrosion research has been analyzed quantitatively using bibliometric methods. Altogether 577 highly cited articles from 1938 to 2010 were mainly published in 1990s and 2000s. C*orrosion Science*, *Journal of the Electrochemical Society*, C*orrosion* and *Electrochimica Acta* were the core journals. Multidisciplinary materials science, metallurgy and metallurgical engineering, electrochemistry and coatings and films materials science were the four most productive categories, while corrosion research is closely related to research areas of technology and physical sciences. The seven industrialized countries were the dominators in this field, while the USA held its primacy. Most countries had more independent than collaborative publications, especially Japan. Meanwhile, Tohoku University of Japan took the lead, exhibiting a strong ability of independent research. The total citations since publication to 2012 (TC_{2012}) has a significant correlation with annual citations per article (TCPY) and citations in 2012 (C_{2012}). Inoue, from Tohoku University of Japan, contributed to the most cited article related bulk metallic glasses in 2000. A continuum model for sensor applications emerged as a new research emphasis in corrosion research field. Furthermore, the peak year of citations per highly cited article was about one decade, longer than non-highly cited articles in other fields. Impact factor do not display a strong correlation with the cited times of highly cited articles.

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