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TECHNICAL CERAMICS AND REFRACTORIES APPLICATIONS AND VOLUMES LITERATURE REVIEW

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ABSTRACT

Daniel Kujanen: Technical ceramics and refractories applications and volumes literature review
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Refractories are ceramic materials with high melting point and can withstand stress at high temperatures. They are important materials for large industries with high temperature processes. Technical ceramics are modern day ceramics with applications focused more on technical and medical applications. This thesis examines the markets, production volumes and applications of refractories and technical ceramics. The main goal is to collect and analyse market data to find different factors that have an impact on these markets.

This thesis is divided to three parts. Basic information about the ceramic industry is first explained in the text. Refractories and technical ceramics are discussed in more detail in the following sections. These sections include market values and production volumes of these ceramic materials, their applications in the biggest end-user industries and future industry forecasts. Future forecast sections review the latest industry trends and new technologies in the industry. The sources used in the study contain literature on materials science, international trade statistics, market reports and reports from companies and associations in the industry.

As a result of this thesis, information on the values and volumes of refractory materials and technical ceramic markets was obtained. Market data and industry associations' reports made it possible to draw conclusions about the factors affecting the market for refractory ceramics and technical ceramics. In addition, this thesis presents current trends, new technologies and the current situation of these industries.

Keywords: ceramics, technical ceramics, refractories, applications, market survey

PREFACE

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Daniel Kujanen

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1. INTRODUCTION

Technical ceramics and refractories are important to modern society. They make up a large share of the global market for ceramic materials. The production volumes of refractory ceramics are very high as they are important for the steel industry. Information on applications of refractories and sources for refractory raw materials are important to refractories manufacturers who aim to develop their operations. The development will help create better products and take advantage of new technologies in the industry. Technical ceramics are the fastest growing sector in the ceramic industry. Technical ceramics offer special properties for many different applications. These materials can be utilized in applications where other materials are not suitable. Technical ceramics enable the emergence of new technologies in many industries.

At the beginning of this thesis the reader is introduced to the ceramics market and the classification of ceramic materials. This thesis focuses on the basic definitions and classification of refractories and technical ceramics, their market values, production volumes and applications of these materials. In addition, future trends of these industries are discussed in this text. Basic definitions give the reader an idea of what refractories and technical ceramics are. Literature on materials science has been used as a source for definitions and classifications. Market values and production volumes of these industries have been gathered from many different sources. Market data have been obtained from reports from market research companies, ceramic industry companies and ceramic industry associations. The text also goes through the key factors that affect the markets in these industries. Applications of refractories and technical ceramics are focused on the major end-use industries of these materials.

2. GENERAL

Ceramics are one of the four main material groups. Ceramic materials are typically considered as hard but brittle inorganic solid materials that have relatively high stiffness. In materials science, ceramic materials are defined as either amorphous or crystalline materials containing covalent or ionic bonds between metallic and non-metallic atoms. [1] Ceramics are most often metal oxides, carbides and nitrides. Ceramics typically have low electrical conductivity and resist higher temperatures and adverse environments better than metals and polymers. [2] Humankind has consumed ceramic materials for centuries. Today, ceramic products are widely used for different applications ranging from tableware to advanced medical products.

2.1 Overview of the European ceramics industry

According to the European Ceramic Industry Association (Cerame-Unie), the European production value of ceramic materials was EUR 30 billion in 2017. The production values estimated by Cerame-Unie are listed in table 1 by application of ceramic products.

Table 1. *Ceramic materials production value in Europe by application, 2017. [3]*

Application	Value (M€)
Wall & floor tiles	9,300
Bricks & roof tiles	6,000
Refractories	5,100
Technical ceramics	2,400
Abrasives	2,700
Table & ornamentalware	2,100
Sanitaryware	1,800
Clay pipes	300
Porcelain enamel	300
Total	30,000

Construction materials and refractories account for the largest share of the European ceramics market. This is due to the growing need of refractory materials for high temperature processes and the continuous demand of ceramic tiles for construction. The high production value and volume of constructional ceramics use is because ceramic materials have been used as an affordable alternative for metallic construction materials. Refractories are also a huge market sector in the ceramic materials business. The consumption of refractory ceramics is very high especially in industries with high temperature processes and high production volumes. Steel industry is the biggest consumer of refractory ceramics.

2.2 Classification of ceramic materials

Generally, ceramic materials are categorized to two main groups: traditional ceramics and technical ceramics also known as advanced or engineered ceramics. Technical ceramics are utilized for various applications, but the production volumes of technical ceramics are much lower than the production volumes of traditional ceramics.

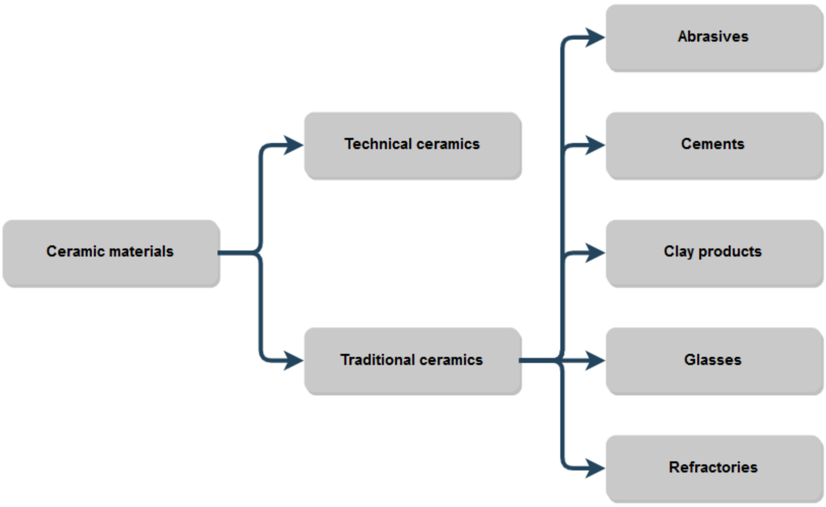

Figure 1. *Classification of ceramic materials.*

Ceramic materials market consists of traditional and advanced ceramics market. The market for traditional ceramics consists of high-volume products such as construction materials (cement and tiles), whitewares, refractory materials and abrasives. Figure 1 shows the commonly used classification of ceramic materials. Ceramics can also be classified to four groups by their chemical composition. These groups include clay ceramics, oxide ceramics, nitride ceramics, and carbide ceramics

Ceramic products are conventionally made from clay. This includes structural clay products, whitewares and refractories. Cement, abrasives and glass products are made from different kinds of mineral matter such as lime, silica or alumina. Silica and alumina have also been utilized in production of refractories and technical ceramics. Technical ceramics and refractories will be discussed in the following chapters.

3. MARKET SURVEY FOR REFRACTORIES

Refractory material is a type of ceramic material that can resist high temperatures, adverse atmospheres and liquid slags. In materials science, the definition of refractory material is based on the melting point of pure iron (1539 °C). Refractory material maintains its shape and strength in temperatures clearly above this point. [1] Refractory materials are important materials to all high-temperature industrial processes. They provide high mechanical strength in high temperatures, protection against corrosion and thermal insulation. [4]

Refractory materials have four main functions. They provide thermal insulation and help to retain heat where it is needed. They can be used as thermal barriers between hot medium and the walls of the containing vessel. They keep their strength in high temperatures and reduce the wear of the walls caused by the circulating molten metal. Finally, they provide a chemical protective layer against corrosion.

Refractories are mainly made from ceramic metal oxides such as alumina, silica, magnesia. Usually refractory materials are mixtures of these oxides. Refractories can also be made from non-oxide ceramics like graphite or silicon carbide.

Modern civilization is based on the heavy use of glass, cement and metallic materials. These materials are produced in high temperature processes and these processes require refractory ceramic materials for thermal insulation. Without refractories, there would be no steel, aluminium, glass, cement or chemical industries. Large quantities of refractories are consumed by these industries annually because refractories have a limited lifespan. The demand is constant due to the high consumption of refractories in these industries

3.1 Classification of refractories

Refractories are classified based on physical form, chemical composition, refractoriness and end-use industry. Refractories are divided to two groups by their physical form.

Table 2. *Classification of refractories, by form. [5]*

	Physical form
Shaped	Standard shapes controlled by most refractory manufacturers.
	Special shapes that are specifically made for particular kilns or furnaces.
Monolithics	Unshaped refractories without definite form and are only given shape upon application.

In table 2, the two groups are monolithics and shaped refractories. Monolithics are also known as unshaped refractories. Standard shaped refractory tiles and bricks are used in furnace walls. Special shaped refractories are made for specific applications in kilns and furnaces. Monolithics can be shaped from refractory ceramic powder. They are given their shape during installation by pouring, ramming or injecting and they are fired afterwards. [6]

Refractories can be classified to three groups by their chemical composition. Refractory materials are classified into acidic, neutral and basic due to their interaction with water. [6] These three groups and their descriptions are presented in table 3.

The chemical properties of refractory materials should be considered when designing industrial processes. Molten slag can be either acidic or basic. Acidic slag needs an acidic refractory lining. For example, bricks made of silica work well in acidic environments, but in interaction with alkaline slag, silica bricks will corrode quickly. [7]

Table 3. *Classification of refractories, by chemical composition. [5, 7]*

Type of refractory material	Use	Materials
Acidic refractories	Used in areas where slag and atmosphere are acidic. They are stable to acids but attacked by basic materials.	Silica, Aluminium silicates, Zirconia
Basic refractories	Used on areas where slags and atmosphere are basic. They are stable to alkaline materials but react with acids.	Magnesia, Chrome-Magnesia, Doloma
Neutral refractories	Used in areas where slags and atmosphere are either acidic or basic and are chemically stable to both acids and bases.	Graphite, Chromia, Alumina

Acidic refractories are cheaper to produce than other refractories and are generally used in conditions with lower operating temperatures. Basic refractories can withstand very high temperatures, but they require to be handled appropriately because they are prone to hydration. Neutral refractories are widely used throughout the metal industry because of their ability to withstand both basic and acidic environments, high melting temperature and reasonable price. [6]

Refractory materials can also be classified by their refractoriness. Refractoriness is defined to be the temperature at which refractories fuse. The operating temperature of the refractory product should be lower than this temperature. [5] Refractoriness can be divided to four categories that are presented in table 4.

Table 4. *Classification of refractories, by refractoriness. [5]*

Type of refractory	Refractoriness (°C)
Low heat duty (LHD)	1520-1630
Medium heat duty (MHD)	1630-1670
High heat duty (HHD)	1670-1730
Super duty (SD)	> 1730

Refractories are mainly used by different industries. These industries consume refractory materials to manufacture products for end-user markets. Examples of industries that consume refractories and end-use industries are presented in table 5.

Table 5. *Classification of refractories, by end-user. [1]*

Industries that consume refractories	End-users
Cement and lime production	Building industry
Iron and steelmaking	
Glass industry	Automotive industry
Nonferrous metals production	
Oil and gas industries	
Waste incineration	Other
Basic industries	

Different end-use industries need different materials for production, but almost all of material production needs refractory materials for their high temperature processes.

3.2 Global market

The demand for refractory materials is great due to the importance of refractory materials in all high temperature processes. The growing need for these materials acts as a driving force for the global market. The estimated value of global refractory ceramics market is EUR 20 billion. [8, 9] The volume of refractory ceramic production was estimated at 40 million tons in 2012. [10]

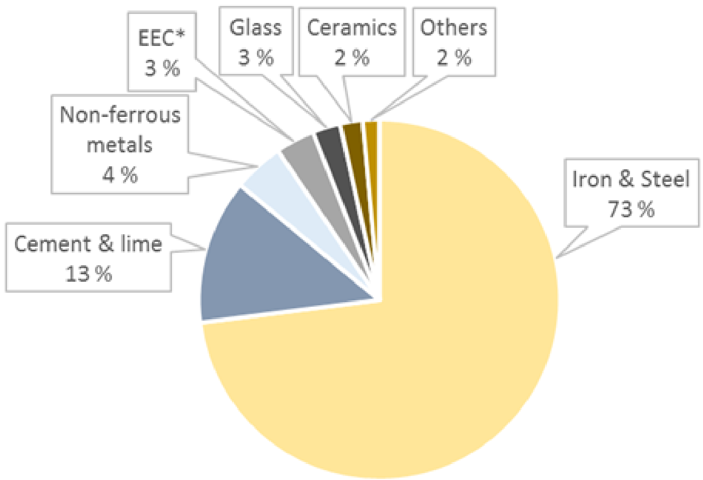

Figure 2. *Consumption of refractories by end-use industry in 2012. (* EEC = enviro-energy-chemistry) [10]*

The biggest consumer of refractory materials is the steel industry. In 2012, the steel industry accounted for over 70 % of the consumption of refractories. The consumption of refractories in 2012 is shown in figure 2.

Table 6. *World refractory demand in kilotons, 2004-2014. [11, 12]*

	2004	2006	2009	2011	2014
Region	**Demand (kt)**	**Demand (kt)**	**Demand (kt)**	**Demand (kt)**	**Demand (kt)**
North America	3,305	3,465	2,445	2,695	3,150
Western Europe	3,550	3,785	2,725	2,960	3,240
Asia Pacific	13,350	21,470	21,340	27,150	27,850
Other regions	5,460	6,530	4,990	6,345	6,460
Total	25,665	35,250	31,500	39,150	40,700

The demand for refractories is the greatest in Asia and Pacific region. Asian countries such as China, Japan and India consume large amounts of refractories yearly for their high temperature industrial processes. The demand for refractories is continuously growing in these countries. In Western Europe and North America, the growth of the demand has been slower than in Asia, but it has increased after the recession in 2008-2009. The global demand values of refractories, which are estimated by the Freedonia Group, are listed in table 6.

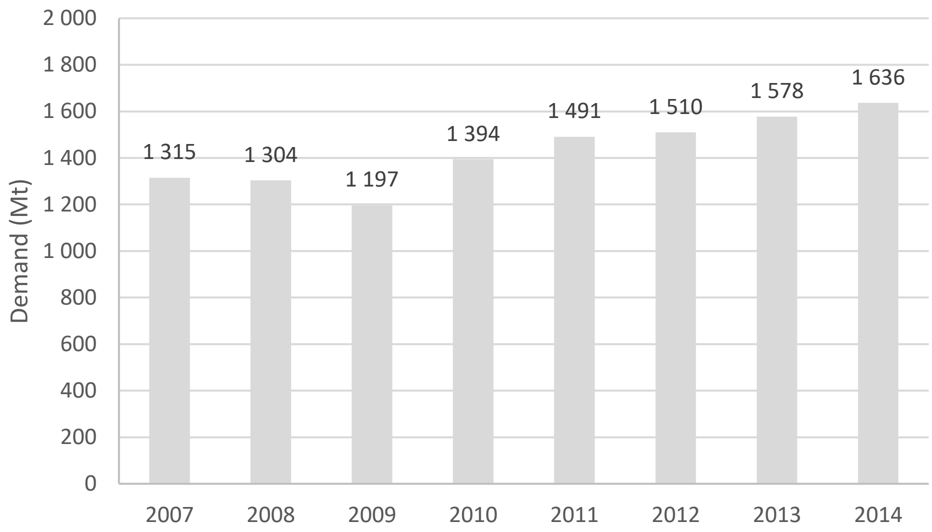

Figure 3. *Global crude steel production and estimate, 2007-2014. [13]*

There is a clear correlation between the refractory demand and the crude steel production illustrated in figure 3. Refractory industry is highly dependent of the steel industry.

The availability of raw materials is also one of the key factors of the refractory ceramics market. The purity of the raw material has a direct impact on the quality of the ceramic product. The most consumed refractory raw materials are refractory clays. Refractory clays consist mainly of silica and alumina.

Table 7. *Global consumption of refractory raw materials. [6]*

Raw material	% of world refractory raw material consumption	Primary source country
Refractory clays	46.0	China
Magnesia	26.0	China
Recycled refractories	7.0	
Calcined bauxite	4.0	China
Brown fused alumina	3.0	China
Doloma	3.0	USA
Tabular alumina	2.0	
Calcined alumina	2.0	China
Other (consumption ≤ 1.0%)	7.0	China

Magnesia is critical to the steel industry. Basic refractory is needed to withstand the basic slag and the high operating temperatures in the steel industry. This is the main reason why magnesia is listed as the second most consumed refractory raw material in table 7.

Table 8. *China's share of the refractory raw materials supplied. (* value includes Guyana controlled by China) [14]*

Raw material	Share (%)
Dead burned magnesia	45
Fused magnesia	90
Refractory bauxite	95*
Silicon carbide	40
Brown fused alumina	50
Graphite	80

As we can see from tables 7 and 8, China is the primary source of refractory raw materials. Refractory producers are highly dependent on raw material imports from China. China's shares of the refractory raw materials market give China the opportunity to control the refractories global market with export taxes and trade restrictions. [15]

3.3 EU markets

Refractory industry is the third biggest ceramic industry in Europe. This can be seen from the values in table 1. Refractories account for 17 % of the ceramic market in Europe [3]. European refractories producers' federation (PRE) estimated that the European refractory industry employs 24,000 people in 2010. The refractory production was approximately 5 million tons and the turnover was EUR 3.77 billion in 2010. [11] The European refractory production accounts for 14 % of the 40 million tons of consumed worldwide. However, the value of the sold production is 17 % of the total value of global refractories market. This is because a great proportion of the production sold is of high-quality refractory products. [15]

Many of the large refractories' manufacturers have their research facilities and headquarters in Europe [15]. Such companies include Vesuvius, Saint Gobain and RHI Magnesita. The main customers for these companies are the European steel, cement and glass industries. European refractories manufacturers export a large proportion of their production. In 2009, 35-45 % of the European production of refractories was produced for export. [8, 11]

The availability of refractory raw materials restricts the growth of European refractory industry. European refractory industry requires high quality raw materials to produce refractory products that meet the high-quality standards set by European industries. The main refractory products produced in Europe are fireclay refractories, magnesia refractories and high alumina refractories [15]. More than 60 % of the raw materials used to produce refractory products in Europe are imported. For example, 60 % of the consumed magnesite and 100 % of refractory grade bauxite is imported. China is the main source of refractory raw materials for European refractory manufacturers. [8] European refractory manufacturers need to ensure their access to raw materials at a competitive price. Otherwise, their competitiveness will deteriorate. One option for European refractories manufacturers is to develop another source for raw materials. [14] This could be accomplished through implementation of secondary raw materials or recycling of spent refractories.

3.4 Price categories for refractories

Raw materials account for 40-60 % of the price of a finished refractory product [8, 14]. The value depends on the purity of the raw material, where the raw material is sourced and which raw material is used to manufacture the product. Refractory raw materials have a great influence on the quality of a finished product and therefore the efficiency of industrial processes [15]. The prices per ton for shaped refractory products such as refractory bricks and tiles are listed by composition to table 9. The values shown in table 9 are calculated from Eurostat's international trade data.

Table 9. *Import prices of refractory bricks, blocks, tiles and similar refractory ceramic constructional goods by composition, in EU28 region, 2016-2017. [16]*

	2016	2017
Composition by weight	**€/ton**	**€/ton**
> 50% MgO, CaO or Cr_2O_3	823	871
≥ 93% SiO_2	1,210	1,430
7% < Al_2O_3 < 45%, > 50% combined with SiO_2	727	743
> 50% Al_2O_3, SiO_2 or a mixture or compound of these products	1,580	1,480
Other compositions	1,120	1,170

Slightly over half of refractories market consists of shaped refractory products. The production of shapes that are more complex and monolithic refractories is growing due to the customers' increased demand of more customizable products. [11]

3.5 Applications of refractories

Refractories are needed in all high temperature industrial processes. The main industries are material production and energy industries. Refractories are consumed large amounts by these industries. The average specific consumption of refractories in Europe is presented in table 10.

Table 10. *Average specific refractory consumption by industry in Europe. [11, 15]*

Industry	kg/ton
Steel	10-12
Glass	4-5
Cement clinker	0.6-0.8
Nonferrous metal	5-10
Waste incineration	5.5

The steel industry consumes significantly greater amount of refractories compared to other industries. The consumption of refractories has decreased from 25-30 kg per produced ton of steel in 1970 to 10 kg/ton in Europe, Japan and the U.S. [6].

The consumption of refractories increases the cost of the manufactured product. Refractory ceramics account only for 1-3 % of the cost added to the finished product. The cost is relatively small compared to the large quantities of refractory materials consumed. Consumption and applications of refractories by different end-use industries are presented in table 11.

Table 11. Main applications, replacement cycles and costs of refractories for end-use industries. (EEC = enviro-energy-chemistry) [9]*

End-use industry	Applications	Replacement cycle	Costs
Steel	Basic oxygen furnace, electric arc furnace, casting ladles	20 minutes to 2 months	3.0 %
Cement & lime	Rotary kiln	Annually	0.5 %
Non-ferrous metals	Copper-converter	1-10 years	0.2 %
Glass	Glass furnace	Up to 10 years	1.0 %
EEC*	Secondary reformer	5-10 years	1.5 %

The reason why steel industry consumes refractories much more than other industries is that the steel industry has several different high temperature processes where they need refractories. Refractory consumption is the highest in applications such as furnaces and converters. The share of refractory types and the consumption of refractories in different applications in the steel industry are shown in table 12.

Table 12. Average specific consumption and product shares of refractory materials in different applications in the steel industry. [11]

Application	Average specific consumption (kg/ton)	Product share	
		Shaped (%)	Unshaped (%)
Oxygen converter	1.2	75	25
Electric arc furnace	5.1	30	70
AOD-Converter	6.2	92	8
Steel treatment ladle	3.3	90	10
RH and DH units	1.3	50	50
Continuous casting	1.2	10	90

Different applications in the steel industry require different refractory materials. As we discussed earlier, the selection of refractory material depends on the atmosphere where the refractory is used. In the steel industry, refractories must withstand contact with basic slag. Therefore, magnesia is the most important refractory material for the steel industry.

Table 13. Refractory materials and their applications in the steel industry. [7, 17]

Refractory material	Application
Silica (≥ 93 wt% SiO_2)	Acidic induction furnaces, Electric arc furnace arches, Continuous casting extension bricks, Coke ovens
Chamotte (30-45 wt% Al_2O_3)	Blast furnaces, Heat treatment furnaces, Pit furnaces, Furnace linings
Alumina (45-56 wt% Al_2O_3)	Ladle linings, Blast furnaces, Pit furnaces
High alumina (≥ 56 wt% Al_2O_3)	Steel treatment ladles, Electric arc furnace arches
Magnesia (≥ 80 wt% MgO)	Electric arc furnaces, Steel treatment ladles, LD- and AOD-converters,
Chrome-magnesia (25-55 wt% MgO)	Electric arc furnaces (above slag), Pit furnaces
Doloma (≥ 36 wt% and ≤ 60 wt% MgO)	Electric arc furnaces, LD- and AOD-converters, Ladles

Applications in the steel industry for different refractory materials are listed in table 13. The materials used in the steel industry consists mainly of basic and neutral refractories, but acidic refractories are still used in some applications.

3.6 Future forecast of the refractory industry

Refractory industry depends highly on the availability of raw materials. The availability of raw materials is a concern for the European and North American industries. The increasing costs and Chinese export taxes lead to the European and North American refractory industries developing new sources for refractory raw materials. Finding new sources for raw materials is difficult. Therefore, the utilization of secondary raw materials and recycled refractories for refractory production has been an important subject for research.

These materials would help to reduce European and North American refractories manufacturers' dependence of imported raw materials and produce more environmentally sustainable solutions.

Circular economy is the latest trend in the manufacturing industries, which seeks to take advantage of all the waste generated by different industries. Industrial waste can be classified to waste energy, waste material and by-products of processes. Waste materials and by-products could be utilized as secondary raw materials to produce new or existing products. For example, mine tailings could be used to manufacture ceramic products like refractories.

Recycling of spent refractories for refractory raw material is an opportunity for companies to reduce the amount of imported raw material used in their processes. A large volume of spent refractories is generated annually. Approximately 28 million tons. Before the recycling of refractories started in the 1980s, spent refractories were exported straight to landfills. The recycling of refractories started due to the increased environmental awareness and increased costs for waste disposal. [6] At first, recycled refractories were used for low value applications such as roadbed aggregates and slag conditioners in the steel industry. This can be considered as open loop recycling. The EU funded REFRASORT project studied possibilities to sort and reuse spent refractories for more valuable high-grade applications. One of these applications was to reuse spent refractories as a recycled raw material for refractory manufacturing. This is called closed loop recycling. [18] The life cycle of refractories is illustrated in figure 4.

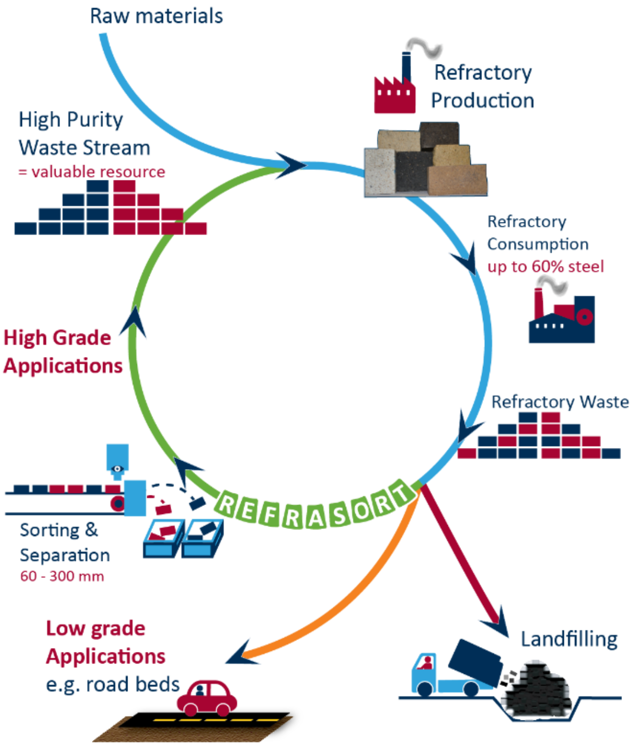

Figure 4. *Life cycle of refractory materials. [18]*

Recycling of refractories is not yet so common because the sorting of the materials is so difficult. Also, the quality of recycled refractory raw materials is not in line with high quality requirements for refractory products. [6]

The market for monolithic refractories has grown a lot faster in comparison to shaped refractories. Monolithic refractories are preferred because of the availability of customized complex shapes and faster installation. However, the properties of refractory bricks are still better than monolithics. [19] The improvements of lining and repair techniques and new binder systems for both monolithics and refractory bricks will be next development steps for refractory manufacturers [11].

4. MARKET SURVEY FOR TECHNICAL CERAMICS

Technical ceramics, also referred to as engineering ceramics or advanced ceramics, are synthetic inorganic compounds, such as oxides, carbides and nitrides, that exhibit superior material performance in certain applications. Technical ceramics can be utilized in several applications that require high mechanical strength and chemical resistance. In electrical applications, technical ceramics are used for semiconductors, insulators, piezoelectrics and superconductors. [1]

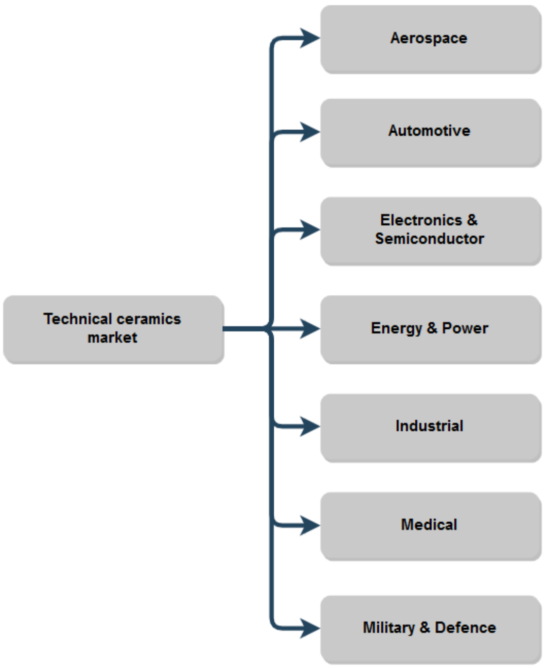

Figure 5. *Technical ceramics market, by end-use industry. [20]*

Technical ceramics market has great potential to grow as the range of different applications is expanding. The employment opportunities in the field of technical ceramics is increasing especially in automotive, electronics and medical industries. [21] The seven main end-use industries of technical ceramics market are shown in figure 5.

4.1 Global market

According to BCC research, the global market of technical ceramic materials was valued at $5.7 billion in 2017. The volume of global technical ceramics market was 363 kilotons. The values and volumes of global technical ceramics market are listed in table 14. BCC research had gathered the values from technical ceramics manufacturer’s annual reports and financial statements. The values represent the value and volumes of the sold production.

Table 14. *Global technical ceramics market values and volumes by region, 2016-2017. [20]*

	2016		2017	
Region	**Value (M$)**	**Volume (kt)**	**Value (M$)**	**Volume (kt)**
Asia-Pacific	2,070	141.0	2,260	152.0
North America	1,480	89.9	1,610	96.8
Europe	1,310	83.1	1,420	89.5
Middle-East & Africa	254	9.0	270	9.6
South America	149	14.3	160	15.2
Total	5,270	337	5,720	363

With almost 40 % share of the global technical ceramics market, Asia-Pacific region is the market leader due to great growth in electronics industry in Asia. The global market shares are illustrated in figure 6. The demand for ceramic materials with unique electrical properties is increased by the development of the industry. China, India, Japan and South Korea have largest shares of the Asia-Pacific market. One of the biggest manufacturers of technical ceramics in Asia-Pacific region is Kyocera Corporation. [20]

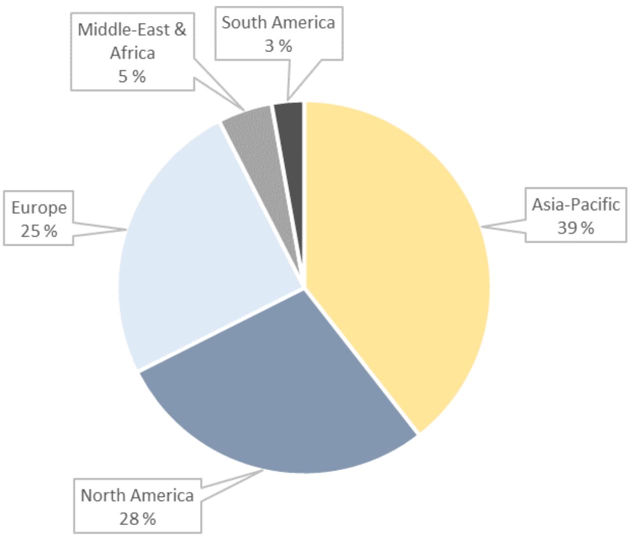

Figure 6. *Global technical ceramics market share, by region, 2017. [20]*

North America and Europe are the next major market areas with a combined share of 53 % of the global market. The global market shares are shown in figure 6. North American market includes United States, Canada and Mexico. Construction, automotive and medical industries are the main applications for technical ceramics in North America.

The consumption of technical ceramics is on the rise. Global consumption grew by 7.7 % from 2016 to 2017. The growth of technical ceramics market is due to the high demand from automotive, electrical and medical end-use industries. [22, 23]

4.2 EU markets

BCC research estimated the European market value for technical ceramics to be at 1.2 billion EUR ($1.4 billion) in 2017. Europe has third largest share of the technical ceramics market. The European technical ceramics market values and volumes broken down by region are listed in table 15. Technical ceramics are most used in the automotive industry, as there are several car manufacturers in Europe. Energy and power industries have also a big demand for technical ceramics. [20]

Table 15. *European technical ceramics market values and volumes by region, 2016-2017. [20]*

	2016		2017	
Region	**Value (M€)**	**Volume (kt)**	**Value (M€)**	**Volume (kt)**
Germany	255	18.9	277	20.4
France	169	12.5	183	13.5
United Kingdom	148	11.0	160	11.8
Russia	208	15.4	226	16.6
Rest of Europe	341	25.3	370	27.2
Total	1,120	83.1	1,217	89.5

There are several technical ceramics producers in Europe. The largest manufacturers of these are CeramTec GmbH, from Germany, Morgan Advanced Materials, from the United Kingdom and Saint Gobain Ceramics Materials, from France. The impact of these large manufacturers in Europe can be seen in figure 7.

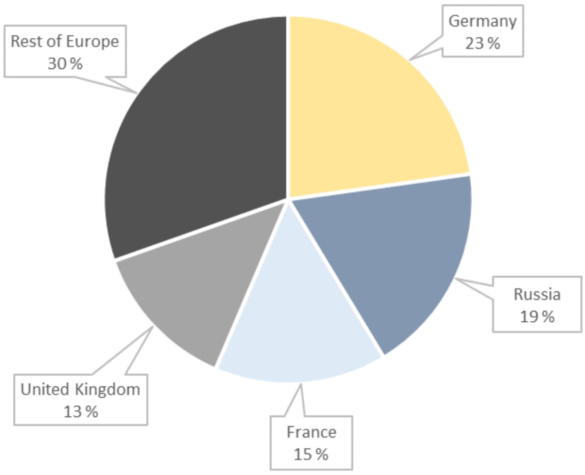

Figure 7. *European Technical Ceramics Market Share, by Region, 2017. [20]*

Saint Gobain is one of the largest manufacturers of glass and engineered materials, such as abrasives and ceramics. Morgan Advanced Materials is an engineering company that provides technical ceramics for automotive, industrial, medical, marine, aerospace and rail applications. CeramTec GmbH is a German company whose focus is on manufacturing products for vehicle and automotive engineering, electronics, energy and environment, mechanical engineering, medical technology, defence systems and chemical industries. [20]

4.3 Price categories for technical ceramic raw materials

The prices for different technical ceramic products can vary a lot depending on the raw material chosen. Ceramic raw materials are generally cheap and readily available, but in some cases raw materials are expensive. The high cost of these raw materials is due to lack of availability. The average import prices of four commonly used technical ceramic raw materials are listed in table 16. The values have been calculated from Eurostat's raw materials import data.

Table 16. *The average price per ton of technical ceramic raw materials imports in EU_28 region, 2016-2017. [24]*

	2016	2017
Material	**€/ton**	**€/ton**
Alumina	335	395
Silicon Carbide	1,110	1,050
Boron Carbide	12,800	15,900
Tungsten Carbide	26,800	29,600

Alumina and silicon carbide are the most commonly used raw materials for technical ceramics. The high consumption of these materials is due to their versatile properties and the affordability of raw materials. Alumina is one of the most widely used ceramic material. It can be used in refractories and abrasives, but also for cutting tools and machine parts. The price of silicon carbide for technical applications is higher than the value presented in table 16. The major application for silicon carbide is in abrasives. Silicon carbide used in abrasives is not suitable for technical ceramics and is therefore cheaper. [21, 25] Due to the affordability of these materials, they can be utilized in both high and low value applications.

The more expensive raw materials are utilized only in high value applications. Tungsten carbide and boron carbide are extremely hard, corrosion resistant materials that can withstand high temperatures maintaining their hardness. Tungsten carbide is used for tools and machine parts that are subject to severe abrasion. [21] Boron carbide is used in nuclear reactors as a shield for neutrons because of its high refractoriness and hardness. [1, 25]

4.4 Volumes for selected applications

Technical ceramics have many applications in different industries. The demand for technical ceramic components in end-use industries is growing as new technologies and applications are being developed. Global market values and volumes for technical ceramics in different end-use industries are listed in Table 17.

Table 17. Global technical ceramics market values and volumes by end-use industry, 2016-2017. [20]

	2016		2017	
End-Use	**Value (M$)**	**Volume (kt)**	**Value (M$)**	**Volume (kt)**
Automotive	1,910	122.0	2,080	132.0
Medical	567	36.1	620	39.4
Electronics & Semiconductor	505	32.5	548	34.8
Energy & Power	936	60.0	1,011	64.2
Industrial	627	40.1	678	43.0
Aerospace & Defence	491	31.3	536	34.1
Others	232	14.8	248	15.7
Total	5,270	337	5,721	363

As we can see from table 17, the automotive industry and the energy industry are the biggest consumers of technical ceramics with over 50 % share of the global consumption. Technical ceramics offer different special properties for different end-use industries. Low density, hardness, electrical properties, corrosion and thermal resistance are reasons why technical ceramics are important to end-use industries. All the transportation related industries benefit from the use of ceramic materials. Ceramic materials offer lower weight than metallic materials, resulting to savings in fuel and increase in company's profits. In addition, the military sector is interested in the increased payload, operating range and manoeuvrability. The electronics and semiconductor industries benefit from the special electrical properties of these materials.

4.4.1 Automotive industry

Automotive industry is the biggest end-use industry for technical ceramics. The global market for technical ceramics in the automotive industry was valued at $2.08 billion in 2017. Asia-Pacific region has the largest share of the market by $820.5 million while the market in Europe was valued at $518.2 million. The global market volume was valued at 132,000 metric tons. [20]

In the automotive industry, technical ceramics are used as an alternative for metals and plastics. Technical ceramics offer better strength to weight ratio and better wear resistance compared to the most common metals used in automotive industry. Every component of a motorised vehicle has specific technical requirements. These requirements have an impact on the material selection. Material selection is driven by cost efficiency, performance and reliability of the component. Components made of high-quality technical ceramics can operate in certain applications where components made of metal or plastic cannot fulfil their requirements.

In the automotive industry, advanced ceramic materials are mainly used for electrical components, engine parts, brake discs and sensors. Probably the best-known advanced ceramic component of a motorised vehicle is a spark plug made of alumina. The most common ceramic products used in the automotive industry are listed in table 19.

Table 18. *List of different applications for ceramics products in the automotive industry. [26]*

Application	Products
Sensors	IR sensor housing, lambda sensors, piezoceramic discs
Body construction	Forming tools, centring pins for welding
Engine control	Valves, valve shims, rocker arm coatings, spark plugs, glow plugs, turbocharger rotors
Cooling water pump	Sliding rings
Battery & electronics	Separators, protective coatings, circuit boards, capacitors
Brake system	Brake discs
Clutch	Friction linings
Lighting system	Sockets, insulating tubes, spark gaps, cooling elements

Engine components can be manufactured from monolithic oxide and non-oxide ceramics as well as ceramic composites. Engine components have strict tolerances, the components require resistance to mechanical and thermal stresses and the components need to be as light as possible. With the use of advanced ceramics in the automotive industry, the consumption of lubricants and fuel is minimized and with this, the harmful emissions can be cut down to minimum. [26]

4.4.2 Energy & power industry

The energy and power industries are the second largest consumer of technical ceramics. The market value of technical ceramics consumed by these industries was $1.011 billion in 2017. The main applications of technical ceramics in energy industry are in power distribution, fuel cells, nuclear power, oil and gas power, wind power and batteries. Technical ceramics for such applications are selected based on their specific properties. In the energy and power industries, the special features of technical ceramics include: mechanical strength in high temperatures, electrical properties and wear, corrosion and thermal shock resistance. [27]

Fuel cells are an effective way to produce electricity from chemical energy. [28] The durability and chemical resistance of fuel cell components are essential to these systems, because the operating conditions require low thermal expansion, high thermal and mechanical strength and the components must withstand oxidizing or reducing atmospheres depending on which side of the cell the component is used. [29] Anodes, cathodes and electrolytes are made from technical ceramic materials to meet these requirements.

An alternative to power generation is energy storage. Technical ceramics are used as solid electrolytes in solid state batteries. These ceramic electrolytes are made from high grade beta alumina tubes. Solid ceramic electrolytes are used instead of liquid electrolytes because they are not flammable. [30, 31] The use of technical ceramics could greatly lower the weight of batteries and improve battery efficiency and safety. As a result, technical ceramics enable significant technological leap in the development of batteries for electric vehicles.

4.5 Future forecast for technical ceramics

Technical ceramics industry is on the rise due to the high demand for high performance components and the development of new ceramic technologies. The demand for technical ceramics is growing the most in electronic and medical industries. One of the main drivers of technical ceramics market is the growing need to replace products and components made from plastics and metals. In addition, the exceptional properties of technical ceramics act as a driver for the growing interest for these materials. [20, 32]

Technical ceramics market has the potential to grow, as the manufacturing costs are decreasing, and the production is becoming more profitable. The increasing dependency of electronic components, such as semiconductors, shows that there is a great demand for technical ceramics in the future. The implementation of technical ceramics is growing, especially for the electronics and medical industries. [32]

Technical ceramics market growth is relatively slow because of the high production costs compared to metals. The raw materials can be cheaper than metals, but the production processes require high temperatures, huge amounts of energy and the machining of these hard and tough materials is not cheap. [33, 34] These are main reasons why the production volumes are low and the unit cost for advanced ceramics is high. Reducing manufacturing costs is crucial to commercialization success of advanced ceramic products.

The current trend of advanced ceramic materials is the implementation of nanotechnology. There is a great potential for medical and electronic applications. Nanoceramics are increasingly used in manufacture of high-speed computer chips and artificial organs and bone implants. Nanoceramic technology has also been introduced in high-performance coatings. These coatings offer the superior surface properties to engineering metals that need better surface quality. Nanoceramic technology is growing, but the growth is hindered by the same problems that have an impact on the advanced ceramics market. [35]

The production of technical ceramic materials is facing a new revolution as 3D printing, also known as additive manufacturing, has had many advancements in the last decade. 3D printing of technical ceramics will offer new possibilities to manufacture complicated components for completely new applications. [36] 3D printing does not require expensive tools and the production process is simplified. Additive manufacturing is an attractive alternative to conventional ceramics production because of its relatively low setup costs. Lower setup costs make the production of advanced ceramics more accessible. Additive manufacturing does not replace traditional manufacturing methods of technical ceramics but has its own applications in the medical and aerospace industries where the demand for new technology is the greatest. For example, the production of dental products, such as braces, prostheses, crowns and bridges, could be the key to start manufacturing customizable ceramic products for personal use. For aerospace industry, the use of 3D printed advanced ceramic products allows to have lighter and stronger components than those produced using conventional manufacturing techniques. [37]

5. CONCLUSION

The global market for ceramics is large. Ceramics have many applications and production volumes are high. The major applications for ceramics are in the construction industry and refractory industry. Ceramic materials are consumed large quantities in these industries because the raw materials are cheap. Despite the cheap price, ceramics have unique properties that are needed for certain applications. For example, low density and high thermal insulation. Ceramic materials can be classified to traditional and technical ceramics. Traditional ceramics include abrasives, cements, clay products, glasses and refractories. The production volumes of traditional ceramics are high, and the production costs are low. Technical ceramics are high-value products but have a low production volume.

Refractory ceramics are important to modern industries, mainly used in material production industries and waste incineration. Refractory industry is also related to other industries, because without refractory materials there are no raw materials for manufacturing industries. Refractories account for the second largest share of the ceramics market after constructional ceramics. The production volumes are huge because steel and non-ferrous metals industries consume large quantities of refractories annually. Due to a variety of high-temperature processes, the steel industry is the largest consumer of refractories. Therefore, the production volumes of refractories are greatly affected by the steel industry.

The refractories market is the largest in Asia. This is for two reasons: refractory raw materials come mainly from China and the demand for refractories is great because of the large material production industries in Asia. China has the control of the global refractories market because it is the source for refractory raw materials. This is causing difficulties for European and North American refractories producers. European manufacturers have been trying to develop alternative sources for refractory raw materials to keep their competitiveness. One alternative source for raw materials is to make use of spent refractories. Millions of tons of refractory waste are generated annually. The lifecycle of refractories could be considerably longer, and the materials would be more valuable if they could be recycled into refractory raw materials. Carbon footprint of refractory products can be reduced by extending the life of refractory materials by recycling spent refractories. The recycling of refractory materials can also be considered from an economic point of view. Reuse of used raw material does not require raw material extraction and transport costs are reduced. The product can be manufactured from sorted recycled raw-materials near the end-use site. Recycling of spent refractories and extending the life cycle of refractories will be important focus points for sustainable development in the refractory ceramics industry

The market for technical ceramics is much more diverse than the market for other ceramic materials. There are many applications for technical ceramics because the properties of the products depend on the raw material and the processing. The properties of technical ceramic products may vary greatly depending on the application. Technical ceramics have big market value compared to the production volume. The market value is big because technical ceramic products are usually targeted for high-value applications. The production volume is low due to high costs of production processes. The price of raw materials can also affect the production volumes. Prices of technical ceramic products vary greatly depending on the raw material used.

The biggest consumers of technical ceramics are the automotive industry and the energy industry. The consumption of technical ceramics is high due to the large number of applications in these industries. On the other hand, the development of technical ceramics is faster in the medical and military industries. There are many areas for development in medical and military industries and new technologies could be utilized immediately. Only restriction to rapid utilization is the setup costs for technical ceramic production. Therefore, 3D printing is becoming more common in the manufacture of technical ceramics. 3D printing allows to create unique products without expensive setup costs. The development of technical ceramic 3D printing technology can greatly increase the demand for technical ceramic products and create new competition in the industry.

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