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Techno-economic modeling in advanced ceramic materials manufacturing using Spark plasma sintering technology

Mmakwena. C Tsipa and Mukondeleli. G Kanakana

Department of Industrial Engineering

Tshwane University of Technology

Pretoria, 001, South Africa

tmktsipa@gmail.com, KanakanaMG@tut.ac.za

Abstract

Prior to commercializing a product of interest, techno-economic principles are used to determine viability of the process flow. The aim of this paper was to conduct a desktop research on the process flow of interest (the technology and the raw material of interest) using techno-economic approach thereby determining the commercializing a product. As much as Silicon Nitride based materials that are sintered through the application of Spark Plasma Sintering SPS technology have grasped the interest of researchers for commercial possibilities, a techno-economic study of commercializing Silicon Nitride based materials using SPS technology was not found during the desktop research. The results obtained indicated that there is a common agreement among authors about techno-economic application. It was therefore concluded that techno-economic approach/ principle(s) can be used to determine the commercialization of any product.

Keywords:

Techno-economic,

Spark Plasma,

Powder metallurgy

1. Introduction

Spark Plasma Sintering (SPS) technology was first developed by FCT Systeme GmbH in Germany, for the production of powder metals, ceramics products and as a replacement for the traditional method of sintering, that being, Hot isostatic press (HIP) and Hot press (HP). SPS has been a growing technology that was further manufactured by the United States of America, Japan and China (Guillon, 2014).

James, (2017), indicated that Powder metallurgy (PM) as a method of processing metal powders of specific shapes and size had improved specimen properties through the use of SPS technology as compared to the traditional methods. PM was inspired by the deficiencies that were experienced in the traditional method of metal casting, and the inability of the casting method to producing required sized and shaped parts

PM was introduced as a solution to stand in the gap that the casting method could not fill. In PM, traditional methods of sintering such as (HP) and (HIP) were used, but the economic viability were not as friendly until SPS technology was introduced (Berroth, 2010). The incorporation of SPS in the PM process flow, showed to be economically efficient while deficiencies that were produced in the traditional methods were either being minimized or eliminated.

By determining a process flow of producing the product of interest, a techno-economic approach can be used to determine the economic viability of commercialization through project investment (Peters, 1991). In the literature review conducted it was shown that the capital investment, working capital, and fixed capital can be determined using different techno-economic principles. The latter includes, cost estimation and profitability measures to determine the viability of production through sensitivity analysis, process optimization and the return on investments. The objective of this paper was to conduct a techno-economic modeling desktop research based on the viability of manufacturing advanced ceramic materials using SPS technology.

This paper has two sections, in which section 1 outlines the processing method, technology of interest along with the raw material of interest, and section 2

outlines the application of techno-economic principles to different processes, and different product commercialization.

Questions that are to be covered in this paper are as follows:

Q1: Can the application of techno-economic principles assist in the economic model of manufacturing silicon nitride based material using SPS?

Q2: Which software's are most suitable for simulating the process flow and its economic viability?

Answers to the questions are shown in Table 1, as a common agreement among authors about the application of techno-economic principles.

2. Literature review

Section 1

2.1.1 Technical content of powder metallurgy

Sintering in PM has been regarded as the most cost effective method of producing highly valued and complex parts that are suitable for the automotive industry, medicine, aerospace and military application. Although the sintering method might have everything to do with the final properties of the specimen produced, the extensive research that has been done showed that the employed traditional method being, HP and HIP can sinter to a limited extend. The limited extensions of the operating parameters are temperature, pressure, the inability to sinter coarse powders, high operating cost, lengthened sintering time and products that needs post sintering finishing processes. In most cases the density of the product is most valued, as other properties are naturally found in the powder of interest, be it a metal or ceramic powder (James, 2017).

In studying some of the operating parameters mentioned, (Berroth, 2010), shows that sintering with lengthened time is somewhat uneconomical due to high temperature, holding time thereby producing undesired properties of the specimen. In such instances desired properties can be improved by mixing two or more compound with different melting points that can be sintered in a short space of time and still produce desired results. Therefore, by measuring the density of the sintered product, the sintering process can be deemed to be poor or good.

Torralba, (2014), points out that the use of high temperature can be avoided by first considering the reduction of powder particles, which will also contribute to the increased density of the product. By reducing the particles size, the surface of the particle become more activated and less energy/low temperature is needed to sinter those powders. If the sintered products are not meeting the desired properties, metallurgical principles of heat treatment can always be employed to improve the properties. If applying metallurgical principles is not meeting the requirements, especially of the density, the product can be plated if conventional sintering was employed (Selvakumar, 2017).

2.1.2 Processing method and raw material of interest

SPS technology has gained much attention as compared to the alternate method of sintering due to less reporting of post sintering treatment of the product from SPS. This is because of its ability to produce specimen with highly valued properties in a short space of time that is economically viable as opposed to the traditional method of sintering.

In his study of SiAlONs (silicon nitride and alumina based materials) (Nekouee, 2016), found that the incorporation of SPS in the processing of PM product has shown to be exceptional in achieving desired results. Due to the high temperature requirements in sintering SilONs to achieve full density, the use traditional method would have accompanied the specimen with undesired properties as per operating parameters. In most cases the undesired properties are further processed by finishing, that being, milling and or laser treatment.

By using SPS to study the characteristics of zirconia carbide based material, (Ozturk, 2017), states that the simultaneous application of quick sintering temperature and pressure improves the way in which particles are packed in the mould, thus improving uniform density. This is of course done by the increased contact points of particles.

The interest in SPS was further investigated by (McNamara, 2017), when he compared the traditional method and SPS. (McNamara, 2017), realizes that when the traditional method was used as a processing method, lengthened time of up to 7 hours were experienced, which means that unnecessary reactions took place and that more energy was required but desired results were not achieved. But when SPS was used, the voltage that produced high temperature was low and shortened sintering time were experienced thus preventing unnecessary reactions to occur.

When reactions start to take place during sintering, undesired properties are produced along with the compound of interest being converted into other compounds that are not of interest. Quick sintering in SPS prevents the conversion of compounds from happening, and in the process desired results are produced (Bahrami, 2017).

As stated earlier that most properties of the products depends on the powder of interest, silicon nitride based materials have shown to have outstanding properties,

due to the natural properties of silicon nitride. Properties such as low thermal expansion, high strength, high temperature resistance, abrasion resistance and more that are of research interest have shown to extend the life of silicon nitride composites (Berroth, 2010).

The latter is also reported by (Bódis, 2017), when a silicon nitride composite of zirconia was investigated for optimum properties using SPS. Before sintering, the powders are mechanically alloyed to a required state, thereafter poured in a shaped mould and placed inside SPS to be sintered. Temperature, pressure, voltage, and the atmosphere are controlled to achieve suitable operating parameters. Since density is high valued in the product, if the product is not fully dense the operating parameters can be controlled to favour full densification.

The operating parameters of any processing method can be of major concern to economical processing. The latter is more concerned with the technical content and the process flow of the method being used to produce desired products, from research or experiments point of view to an industrialized or commercial point of view. Therefore techno-economic methods are used to determine the viability of a technical process flow.

Section 2

2.2.1 Techno-economic background

Techno-economic is a method of determining the economic viability of manufacturing or processing product of interest. The technical part is comprised of process flow modelling, and the product itself has to be of high value to economically maintain the technology being used. While the economic part is more concerned with the economic modelling that is comprised of: the capital investment, profitability measures, and optimal operating conditions for financial purposes. (Peters, 1991) States that, if profitability measures shows that the product cannot sell, the investment interest will not be considered.

2.2.2 Techno-economic application

In attracting investment interests (Lin, 2017), uses techno-economic measure to determine the viability of optimizing a product of interest. In the study a process model that is based on annual performance was simulated to determine suitable operating parameters. The process flow operating parameters were further used to determine the economic viability. The investment cost was estimated by considering the sum of all major equipment cost. And when sensitivity analysis were applied to the conditions, economical optimal operating parameters were obtained.

In obtaining viable economic measure that favours investments interest, different cost estimation methods such as the factorial, exponential, module, quotation requirements and coefficient method can be used (Peters, 1991).

In using a different cost estimating method supported sensitivity analysis, (Han, 2017), uses an Aspen Plus software to simulate the technical process flow of producing a cellulosic g-Valerolactone using lignin derived propyl guaiacol. With the simulated operating conditions, economic viability was measured. By using the software, economic measure of the capital investments, operating cost, and the selling price of the product were successfully obtained.

The application of the Aspen Plus software is also used by (Carrasco, 2017), in simulating the process flow of producing a bio-fuel. In the study carried out, it was states that experimental results were used as the basis of determining the economic viability of commercialising the process. And that the concern of economic challenges were oriented towards the raw material of interest, capital cost, and the life of the processing plant. By using a module cost estimating method, economic viability of the commercial process were obtained after performing a sensitivity analysis that showed that the selling price was affecting the capital investment.

(Zhou, 2016), uses a techno-economic approach to compare the viability of commercially processing shale to liquid and coal to liquid. In the study, an exponential cost estimating method, followed by a straight line profitability measure was carried out to determine the viable process. By estimating the capital investment that is comprised of a fixed capital and a working capital, it was found that the processing of shale to liquid was more economically viable. It was further stated that the purity of the raw material was of concern, and that process optimization can be performed to lower production cost with favourable operating conditions.

In obtaining low production cost with favourable operating conditions, (Tanera, 2017), uses a factorial method to determine the capital investment, working capital, and cost of maintenance in a turbine power plant. (Tanera, 2017), states that by using the method of cost estimation method, the return on investment is determined and that the economic viability is determine by the operating parameters which can be optimized. The latter statement is supported by (Lin, 2017) and (Li, 2017).

In the study of producing jet bio-fuel from corncob, (Li, 2017) states that the process flow energy and mass balanced had an influence on the economic measures. By using the Aspen software, process optimization was simulated using experimental data, and a factorial

cost estimation method was employed along with quotation requirements. By using this hybrid method, total capital investment, operating expenses, direct and indirect cost were determined. In the study, it was mentioned that the technology used could be improved to favouring the economic viability, and that the optimization of the process flow could also be of help in lowering production cost.

By supporting the afore mentioned authors, (Shafiee, 2016), uses Aspen Plus and Aspen HYSYS software's to simulate a process flow of producing hydrogen using a thin layer membrane reactor. The study focuses on commercializing the process, but uncertainties are considered as a challenge of upscaling. By incorporating the use of MATLAB software to simulate process optimization, it is mentioned that uncertainties can be manipulated by changing one operating variable at a time. In so doing, economic measures shows that the technology of interest can be used viably to produce hydrogen.

3. Methodology

Desk top research was conducted, and research papers from year 2010 to date were studied to answer the research questions. The literature review was carried based on the basis of techno-economic, which outlines the technology of interest and its economics. The literature review of techno-economic that was done, showed that there hasn't been an extensive work that was carried out on SPS. Rather techno-economic studies were conducted on different technologies in a processing plants, either from grass roots, development, and replacement level, but not that of SPS technology.

In the review that was conducted, only the literature based on techno-economic (modeling, analysis, evaluation), technology of interest (SPS), and Silicon Nitride was considered to be of interest due to alinement of the study title. Common agreement among authors was analysed and considered to be the baseline that the study would be based on, thereby also answering the question of interest.

4. Results and Discussion

In the literature review carried out, the techno-economic approach of commercializing silicon nitride based material was not found. Although the literature reviewed shows that principle of techno-economic can applied to study the commercialization of any product. This was done by analysing a common ground that appeared in different papers. The latter is shown by Table 1

Table 1. Literature review analysis

Questions	**Techno-economic application common ground**		**References**
	Question 1	**Question 2**	
Can the application of techno-economic principles assist in the economic modeling of manufacturing silicon nitride based material using SPS?	●	●	Carrasco, J.L., Gunukula, S., Boateng, A.A., Mullen, C.A., Desisto, W.J., and Wheeler, M.C., Pyrolysis of forest residues: An approach to techno-economics for bio-fuel production, *Fuel*, vol. 193, pp. 1-8, 2017.
	●	●	Han, J., Process design and techno-economic evaluation for catalytic production of cellulosic g-valerolactone using lignin derived propyl guaiacol, *Journal of Industrial and Engineering Chemistry*, vol. 52, pp. 2,5,6, 2017.
	●		Lin, M., and Haussener, S., Techno-economic modeling and optimization of solar-driven high-temperature electrolysis systems, *Solar Energy*, vol. 115, pp. 2,8,13, 2017.
	●		Peters, M.S., and Timmerhaus, K.D., *Plant Design And Economics For Chemical Engineers*, Singapore: McGraw-Hill. (International Edition), pp. 125, 1991.
	●		Tanera, T., and Sivrioglu, M., A techno-economic and cost analysis of a turbine power plant: a case study for sugar plant, *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 1,5,8, 2017.

	●		Zhou, H., Yang, S., Xiao, H., Yang, Q., Qian, Y., and Gao, L., Modeling and techno-economic analysis of shale-to-liquid and coal-to-liquid fuels processes. *Energy*, vol. 109, pp. 1-8, 2016.
Which software's are most suitable for simulating the process flow and its economic viability?		●	Shafiee, A., Arab, M., Lai, Z., Liu, Z., and Abbas, A., Modelling and sequential simulation of multi-tubular metallic membrane and techno-economics of a hydrogen production process employing thin-layer membrane reactor, *International journal o f hydrogen energy,* vol. 41, pp. 1-15. 2016.

This statement is supported by different authors using techno-economic principles with different process flow/ technical content to determine the viability of commercializing certain products/ processes with respect to specific technologies. The latter statement is emphasized to support the first question of this paper.

The second question was supported by the fact that most of the authors use the same principles assisted by suitable software's for simulation purposes. Although (Peters, 1991) and (Lin, 2017), are not mentioning the application of any software, they emphasize that the application of techno-economic principle are basics of the study. In supporting the latter authors, a techno-economic study can be successfully employed without the aid of software's.

5. Conclusion

According to the techno-economic literature review in this paper a desktop research was successfully conducted. It is therefore concluded that the economic viability of manufacturing/ commercializing silicon nitride based material using SPS can be determined by the application of techno-economic principles without the aid of software(s), unless software's are used for simulation purpose. As much as the raw material is of economic concern in techno-economic, Silicon Nitride was found to have suitable properties of interest for military, medicine, and automotive industry application. It is also concluded that the questions of interest were answered in statements made by different authors presented in Table 1.

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Biography

Mmakwena Tsipa is a 2nd year fulltime student doing a Structured Masters of Technology in Industrial Engineering at the Tshwane University of technology. He hold a Bachelor of Technology in Engineering Metallurgy from the Tshwane University of Technology, with 3 years' experience in the Mineral processing industry.