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# An Overview of the State of the Art and Applications of Sintered Metals

H.O. Onyishi[a,b], C.K. Oluah[a,c]
[a] *Mechanical Engineering Department, University of Nigeria Nsukka*
[b] *Mechanical Engineering Department, University College London*
[c] *Mechanical Engineering Department, University of Johannesburg*

***Abstract:***
*Sintering is a process of manufacturing materials from the powered form. It is employed in manufacturing metals of high melting points to save costs. This paper presents an overview of the process and highlights the applications of metals produced by this process.It investigates the history of the process, highlights its fundamental stages, enumerates the current state of the art, discusses the applications of metals produced from the process and makes forecasts about the future of the process. The traditional types of sintering discussed include pressure sintering, liquid phase sintering and electric current assisted sintering while the areas of applications discussed are general machinery, automotive industry, medicine, jewellery and acoustics. Finally, it is predicated that the range of applications of the process or metals produced therefrom is bound to expand going forward.*
***Keywords****: Sintering, Sintered Metals, high melting point, powder metallurgy.*

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## I. Introduction

Sintered metals are produced by a process which involves heating the (compacted) powdered metal to a high temperature (but below its melting point) such that it bonds together into a solid shape. It is, thus, very beneficial with metals that have excessively high melting points like tungsten, molybdenum, chromium, titanium, stainless steel, iron etc. but which are very useful in many applications. These metals are produced by sintering as casting would involve excessively high temperatures and, thus, production costs. Sintering is also employed in the manufacturing process of Diamond, ceramics and other non-metals with high melting points. In addition, sintering can be employed as a recycling process in that one of the ways of adequately recycling metallic waste, for instance, iron filings, is by sintering.

This articlegives an overview of the state of the art of the technology, especially in metallurgy, and outlines its applications. It gives a brief background of sintered metals, describes, in a concise manner, the technology of sintering, gives the importance of sintered metals in materials selection and makes suggestions for future developments.

Sintered metals are very important in materials science and selection. They have interesting properties like increased tensile strength and hardness and tailored porosity. These properties make them indispensable in many applications including automotive and general machinery, medicine and other applications.

Currently, materials engineers continue to investigate the process with a view to improving the technology to meet diverse demanding applications. They also try to predict the direction of the technology in the near future.

For instance, Shi et al.[1] studied the **spark plasma sinterin**g compaction of nanodiamond, carbon nanotubes, and metal electrodes. The fabricated electrode was used as a heavy metal detection sensor. The merits of the sintered electrode were its low cost and being environmentally safe to use. The results of the characterization showed that the sintered nanodiamond sensor detected heavy metals at speeds way higher than the conventional electrodes.

Also, de CastroGirãoet al. [2] assessed the viability of the alloy, CoCrMo,produced using the direct metal laser sintering technique, in biomedical applications. The CoCrMo alloy has found great application in biomedical implants due to is desirable properties and compatibility with human blood. However, this alloy has always been manufactured by casting and more recently by addictive manufacturing. Findings from this research work showed that the sintered alloy had a comparable corrosion pattern with the conventionally produced alloy, however, the XRD analysis revealed that the sintered alloy had a strain-induced martensitic transformation which enhances sufficiently the ductility and strength of the alloy.

More still, Liu et al.[3] synthesized a combination of graphene and paper-like sintered stainless steel fibers for use as a metal-free catalyst for peroxide oxidation of Phenol in a fixed bed reactor. The graphene coating on the sintered steel performed very well by reducing the pressure drop and improved contact efficiency in the reactor.

Furthermore, Liu et al.[4] posited that manufacturing metal parts by fused deposition modeling and sintering, FDMS, was way cheaper than 3D printing of metals although this approach produced alloys with pores and hence not suitable for manufacturing all types of parts.

Moreover, a double pressing and double sintering approach were employed by Alem et al. [5], for the development of metal matrix composites and nanocomposites. The authors produced samples of carbon nanotubes (CNT), reinforced aluminum nanocomposites, CNT reinforced copper nanocomposites and a few others. Alloys produced from a combination of double pressing and double sintering methods have shown fine microstructures and are very dense, giving them superior mechanical properties. However, the major demerit of this method is the cost of production since it requires a lot of equipment for part production.

On their part, Liu et al.[6] used a pressureless sintering approach to examine the effects of transition metals on the mechanical properties of B4C ceramics. The result showed that transition metals improved the densification of the alloy through second-phase particle distribution throughout the alloy. The mechanical properties were significantly improved when compared to the single-phase B4C ceramics.

In addition, Wang et al.[7]applied the cold sintering-assisted process in the production of bimorph lead zincornatetitanate thick films on metal substrates. the researchers studies 10µm thick lead zincornate titanium (PZT)/Metal composites prepared using the cold sintered process. The outcome of the study showed that the crack and and delamination often developed can be avoided using cold sintering method, this greatly improves the mechanical properties of the alloy.

Meanwhile, simulation and numerical methods have been applied by some researchers in the study of sintering [8-10]. For instance, a simulation study was undertaken by Nandy et al.[8] on the sintering of $AlSi_{10}Mg$ particles in the direct metal laser sintering method. The molecular dynamics approach was used to study the sintering mechanism of the metal powders. The study revealed that during the sintering process, the interfacial atoms had higher mobility than the surface atoms which made the parts produced denser giving them good mechanical properties. The study also revealed that molecular diffusivity was higher in unequal sized particles than equal-sized particle distribution in the metal matrix.

## II. Background

Porous structures exist in natural materials such as wood, bone, cork, coral and sponge [11]. They are essentially lightweight materials and have very useful applications. In the same vein, instances of porous (sintered) metals existing in natural deposits have been reported although sintering became known as basically a manufacturing process in the eighteenth century[11-14]. German [13] reports that there is retrieved evidence (such as shown in Figure 1) of early sintering before 1700 while trial and error sintering happened in the early eighteenth century. Furthermore, early modern theories of sintering started emerging by the turn of the twentieth century before the full-scale sintering practice known today commenced in the mid-1940s[13].

In his account, Fang [15] states that manual sintering started as a craft (called *firing*) which has been practiced since ancient civilizations for many thousand years in the form of pottery, bricks, and art. But there was little or no development in powder metallurgy until the middle of the twentieth century when precision in certain parts of vehicles necessitated the need to consider sintered metals.

Generally, researchers agree that modern metallic sintering started fully in the middle of the twentieth century. Since this time, the industry has grown exponentially what with the expansion of various industries since after World War II [14].

Today, the ever-increasing demands for near-perfect quality and high performance of certain parts of machinery and equipment make sintering still very relevant, if not indispensable, in the materials industry [15].

(a)  (b) 

***Figure 1: Evidence of early sintering: (a) Delhi Iron Pillar (400AD) and (b) Photograph of early goldplatinum decorative medallion. Both made by sintering [13]***

## III. Sintering Techniques (Materials Technology)

Although happening naturally in some mineral deposits, sintering of metals is more commonly known as an industrial manufacturing process or technology called powder metallurgy. The technology basically involves compacting (of powder metal) and forming a solid mass of metallic material by heat and/or pressurewithout melting it to the point of liquefaction. Sintering temperature varies from material to material but is always less than the melting temperature of the base material while modes of cooling and cooling rates depend on the mechanical properties desired [16].

### 3.1 Types of Sintering

Generally, sintering can be classified in different ways depending on the type of material being sintered, the type of heating process used, and the compacting technique used. In terms of the type of material sintered, there are metallic sintering, ceramic sintering and plastic sintering. This article focuses on metallic sintering. Thus, the classification done here is based on techniques employed in metallic sintering. The major traditional (or most developed) types of metallic sintering based on the technique used are briefly discussed below.

#### 3.1.1 Pressure Sintering

Also called hot sintering, this is the most common form of sintering. It involves the pressing of the powder metal into the desired shape, keeping this pressure, heating to desired temperature for bonding to take place and cooling appropriately[14].

#### 3.1.2 Liquid Phase Sintering

Liquid phase sintering involves adding an additive to the powder (to be sintered) which has lower melting point than the matrix phase. On heating, the additive melts and helps to bind the matrix together by capillary action and thereby aiding the proper rearrangement of the grains of the matrix mixture. This type of sintering is commonly employed for materials which are difficult to sinter. The basic requirements for the success of liquid phase sintering are: (a) the matrix phase should at least be slightly soluble in the liquid phase and (b) the additive should have appreciably lower melting point than the matrix phase so as to melt before any major sintering of the solid phase can occur. This technique in sintering has been used to successfully to improve the grain growth of thin semiconductor layers from nanoparticle precursor films [17, 18]. In some texts, it is called pressureless sintering [13]. A special form of liquid phase sintering is known as cold sintering because in this case, the sintering temperature is relatively low [7, 19]. It is usually applied in ceramic sintering but also finds applications in metallic sintering.

**3.1.3 Electric Current Activated/Assisted Sintering Technique (ECAS)**

In this technique, loose powders or a cold-formed compact to be strengthened are put into a container. This container is then heated by electricity to the desired temperature. Holding the container with its contents at this temperature, pressure is applied and kept constant for a given period[20].

**3.2 Stages of Sintering**

Sintering involves four main stages (Figure 2) namely: composition, mixing, compacting and sintering [14]. At the composition stage the alloying compositions of the metallic material can be determined with ease. This makes the process more flexible than other traditional techniques in metallurgy. The mixing stage involves the blending of the metallic mixture to ensure uniform distribution of the different constituents. Compacting and sintering are the final stages whereby the mixture is pressed to desired shape and heated to high enough temperature for bonding to take place. Post-sintering treatment like machining and drilling can then be carried out on the part. The full details of these processes are given in Tsutsui [14], as focus here is more on their applications.

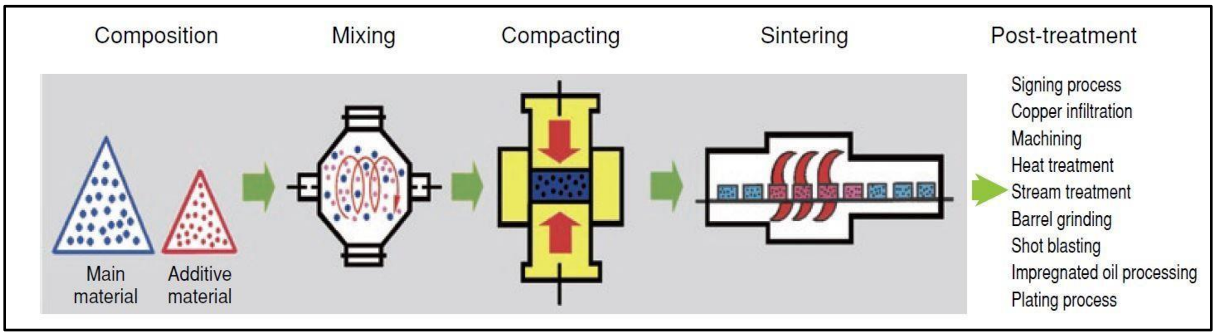



***Figure 2: Stages of Sintering [14]***

**3.3 Properties of Sintered Metals**

Marucci et al [21]showed that the mechanical properties of metals can greatly be improved for desired applications through sintering. For instance, the density, hardness and strength can be improved appreciably to meet industry needs {see Figure 4 (b)}. Kennedy [11]notes that this improvement in material properties of sintered metals is possible due to good control of volume fraction in the obviously porous structure as well as easy manipulation of geometry and sizes of the pores. Figures 3 and 4 show the microstructures of a sintered metal. Some of the properties of sintered metals are discussed below.

**3.3.1 Hardness**

Sintering can be done for the purpose of achieving greater hardness in the material. In this case, the process is called sinter-hardening. Generally, sintering has been shown to increase the hardness of a material. Marucci et al [21]and Rosso et al [22]successfully demonstrated that sintered metals contain mostly Martensite which is the hardest form of a metallic alloy.

**3.3.2 Yield Strength, Tensile Strength, Fatigue Strength and Ductility**

With sinter-hardening, the yield, tensile and fatigue strengths,as well as the ductility, of a metallic material are improved. Rosso et al [22]and Haberberger et al [23] demonstrated that that these properties are higher in sintered metals than in their cast counterparts.

**3.3.3 Density**

The density of the sintered metal is generally lower than that of the cast metal (for the same volume) due to the presence of the pores. It varies with respect to the size of the pores in the metallic structure. This gives sintered metals lighter weights than their cast counterparts [21, 22] and makes them more suitable in applications where high strength to weight ratios are required, like in aircrafts.

**3.3.4 Porosity**

When a piece of metal is desired in a porous form, then sintering is the best approach in manufacturing it. This is because, with sintering it can easily be manufactured with the desired degree of porosity.

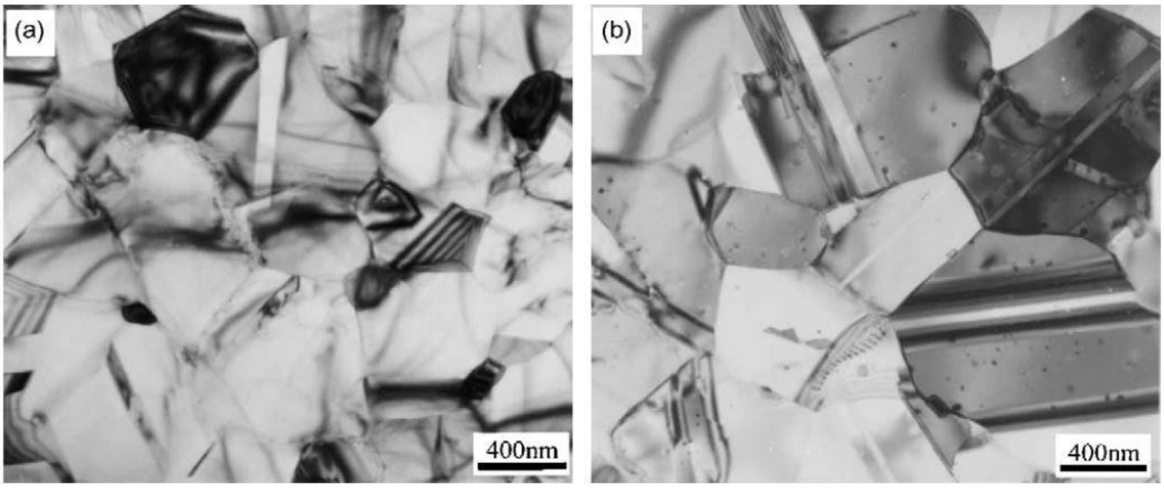
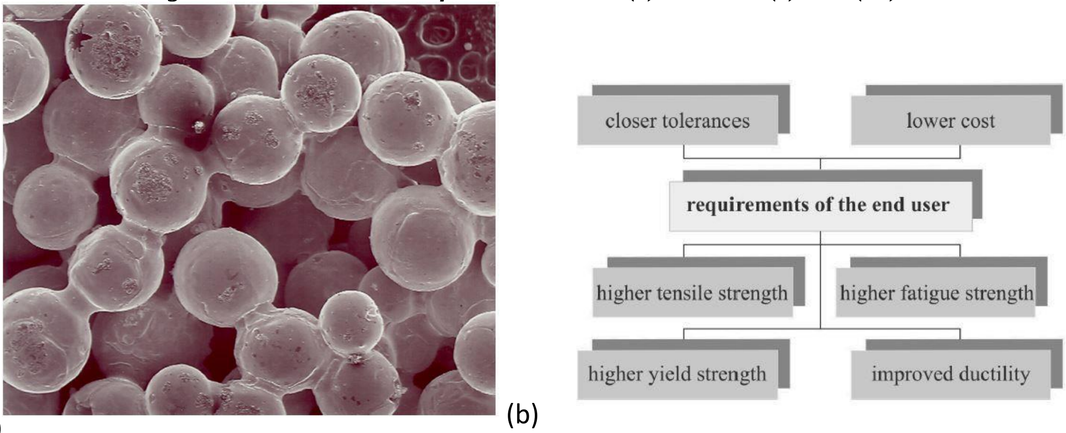



***Figure 3: Microstructure of sintered metals (a) TiAl and (b) TiAl(Cr)[20].***




(a) (b)

***Figure 4: (a) Microstructure of sintered metal (Bronze spheres) from electron microscope. (b) MarketRequirements[13, 22]***

## IV. Applications of Sintered Metals (Material Selection and State of the Art)

Sintered metals have a prominent place in the materials industry as they boast many areas of applications. These include automotive and other machinery, medicine and general applications.

### 4.1Automotive and General Machinery

Sintered metals have many applications in the automotive industry as well as other machinery. According to Tsutsui [14], 90% of powder metallurgy products today are used in the transportation market. Their tailored physical and mechanical properties make them very suitable for making different parts of vehicles and machines as discussed below.

#### 4.1.1Structural Parts

Many parts of vehicles, home equipment, agricultural equipment and other machinery today are made from sintered metals. Over the years, the performance of sintered metals as parts of machinery has greatly increased as has their demand [14]. Most sintered metals used as parts of machinery are alloys of which iron is usually the main material. Sinter-hardened metals are usually more suitable in certain parts than normal sintered metals as these have more desirable mechanical properties. Such parts include gears, pulleys, sprockets and some parts of the suspension system[21]. Figure 5 shows a range of parts that are made from high-strength sintered metals. Tsutsui [14]also reports that sintered metals have` also been used in making parts of an engine with variable valve control systems that help to increase fuel efficiency and that research is ongoing in this regard in the wake of the clamour for green energy technologies.

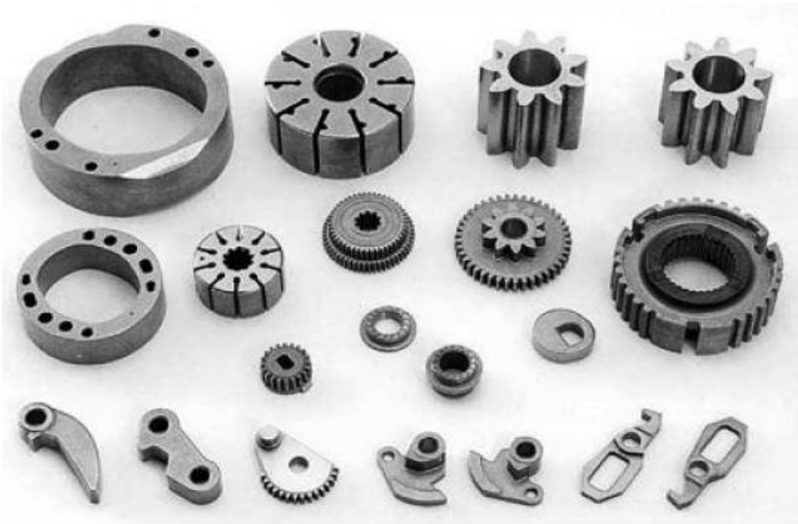


*Figure 5: Range of parts from Sintered Metals[14].*

**4.1.2Sintered Brake Pads**

Sintered brake pads are utilised mostly in motorcycles and have been shown to have higher durability and higher heat tolerance than other brake pads [14]. They are also known to give better results in heavy braking situations. They are usually made from copper by either pressure sintering or belt furnace sintering. They are mostly employed in motorcycles and all-terrain vehicles.

**4.1.3Fluid filtration**

Sintered metals are also applied in the purification of oils, liquid fuels and air that go into the engines of vehicles or sundry machines. This is done by the use of sintered-metal filters mostly in sponge-like structures (see Figure 6) which are made usually from copper, nickel, iron and bronze[11]. For example, sintered metal fibres were used as hot gas filters in a fluid catalytic cracking (FCC) unit of a refinery by Yang et al.[24]. The FCC unit was made to operate at full capacity and the operating conditions and functional parameters were evaluated. With a peak filtration efficiency of 99.55%, they showed that sintered metal fibres are suitable for industrial filtration applications.

Furthermore, sintered metals are well employed for filtering in the industrial and pharmaceutical environments. This is because they boast high filtration capacity, durability and plasticity. They have also been demonstrated to have high shock absorption and contamination prevention for substances being filtered through them. Most sintered metals used in this regard are those made from metal and alloy powders from copper, nickel, iron and bronze[14].

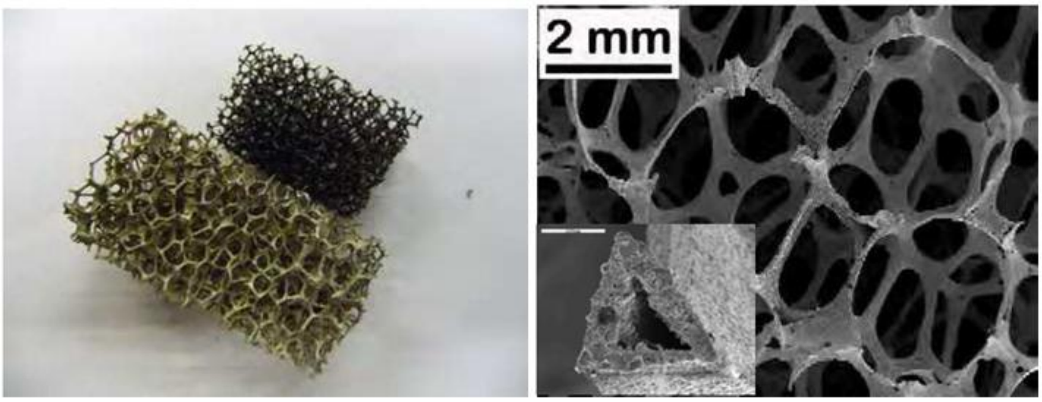



*Figure 6: Sponge-like metal foams produced by sintering used for fluid filtering [11].*

**4.1.4 Exhaust Gas Recirculation and Turbocharging Materials**

Sintered metals have been employed in the exhaust gas recirculation technology of internal combustion engines to reduce NOx emissions and improve fuel efficiency. Furthermore, to ensure a clear exhaust gas and improved

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engine power, turbochargers are installed in many diesel engines. This usually requires heat-and-wear-resistant metals which are usually easily made by sintering. The most common materials for both technologies are based on stainless steel or high chromium cast iron[14].

**4.1.5 Tribological Parts**

Sintered metals have also been greatly utilised in making parts of machinery involved with abrasion and lubrication. A good example is the sleeve bearing. The pores in the sleeve bearing (due to sintering) help them to be lubricated easily while in operation, thus giving them a huge advantage over the other types of bearing. Sleeve bearings are mostly employed in equipment fans used for large chemical and industrial processes. Slightly different from sleeve bearing is another type of bearing called oil-impregnated bearing which is also usually made from sintered metals. Other tribological parts made from sintered metals include high contact pressure bearings, wear-resistant parts and high-temperature, heat-resistant wear-resistant parts [14].

**4.1.6Magnetic Parts**

The underlying objective in many magnetic parts of machinery is to have high permeability and low core loss, thus, saving more energy. Sintered magnetic metals have been shown to meet this requirement very well ([14].

**4.1.7 Lightweight structures**

Lightweight structures made from sintered metals boast excellent stiffness-to-weight ratios and have excellent performance in bending [11]. Lightweight structures have a lot of applications including aircrafts, vehicles, home equipment, bridges and sundry machines.

**4.1.8 Mechanical damping**

Mechanical damping is very important in many industrial machines to avoid failure due to impact loading and fatigue. There are instances where there is no space for traditional dampers in some parts of a machine, but damping is needed, nonetheless. The use of sintered metals in those parts solves this problem. This is because sintered metals have damping capacities that are up to 10 times more thanthose of their corresponding solid metals [11].

**4.1.9Vibration control**

Vibration control is very important in automotive and other machinery. Foamed panels made from sintered metals have higher natural flexural vibration [11] than solid metals. Thus, they control vibration more effectively than their solid-metal counterparts.

**4.1.10 Electric Vehicles**

Sintered metals also find great use in electric vehicle applications. In addition to be used in the making of the chassis and other parts of the vehicles to ensure light weight, sintered metals are also employed in the batteries of electric vehicles to enhance their durability. For instance, Jiang et al [25]carried out an electrochemical study on the performance of sintered metal hydride electrodes for use in electric vehicles. Powder sintered hydrogen storage alloy electrode was produced and characterized. The results presented showed that activation and discharge properties of sintered hydride electrodes were better than those of alloys produced using the conventional casting methods.

**4.2Medicine**

**4.2.1 Metal Crowns**

A metal crown (dental crown, so to say) is used to cover the tooth of a patient with the aim of restoring tooth shape and strength. It is cemented on the gum, covering the exposed area of the tooth. Sintered metals are employed in making both metallic and ceramic dental crowns [18] even though they have limitations in casting and, therefore, may present fitting problems.

The clinical benefits of metals fabricated with direct metal laser sintering technology were presented by Chaar et al.[26]. The long-term clinical results of posterior metal-ceramic crowns produced using laser sintered technology was presented in their study. The observation period was 10-15 years. The survival rate of the crowns averaged out at 81% after 14 years.

***Figure 7: A sample of study crowns; (a) 6 months into the study (b) after 13.5 years. Done by Chaar et al.[26]***

**4.2.2 Biocompatible Inserts**

Sintered metals are also employed in making biocompatible inserts in medicine and surgery. Their cellular texture enhances cell growth[11].

**4.3General Applications**

**4.3.1 Acoustic absorption**

Use of sintered metals in enclosures where acoustic absorption is necessary has proven very effective. Open cell metal foams made from sintered metals have high sound absorption capacities[11].

**4.3.2Energy absorbers (packaging)**

Sintered metals have high ability to absorb energy at constant pressure [11]. Thus, they are used in packaging products where exchange of energy with the surroundings is highly undesirable. They are also used as radiation shields [13].

**4.3.3Heat exchangers**

Sintered metals can as well be used as heat exchangers. Their open-cell foams have large surface areas for cell-wall conduction [11]. As a result, they are excellent materials for making heat exchangers.

**4.3.4Jewellery, arts and sculptures**

Sintered metals are also employed in making jewellery, arts and sculptures from high-melting point precious metals (See Figures 1 and 8). Sintering is employed by artists and sculptors in making artefacts like fired beads, amulets, earthenware vessels and figurines [12].

(a)  (b) 

***Figure 8: (a) Wedding Ring from Tungsten Carbide. (b) Jewellery from Goldie Bronze. Both sintered.[13, 27]***

## V. Suggestions for Future Developments

a. It is predicted that there would be more demand for sintered metals for turbocharging and general exhaust gas abatement technology in the near future[14]. It is thus pertinent that investments in powder metallurgy regarding this be made to meet the demand in the near future.

b. Nickel and molybdenum are two elements usually added in alloys (especially steels) to improve strength and hardness [14]. However, the prices of these metals are very high. This results in increased prices of parts made with them. But chromium is relatively cheaper and can effectively improve the strength and hardness of a few alloys. However, chromium is known to oxidise easily and thus, the technology to contain this quick oxidation must be developed in taking this option. Thus, the powder metallurgy industry must pay attention to this.

c. Sintered metals, despite their many applications, have many limitations including susceptibility to cracking and blistering [13] and limitation in certain castings like the metal crowns mentioned above. In addition, certain levels of precision are yet to be achieved in certain tribological parts [14]. The powder metallurgy industry must thus continue to work towards overcoming these challenges.

d. It is a fact that electronic controls in cars and machinery are becoming more and more advanced and the demand for sintered magnetic materials is on the increase. As such, and with electric and hybrid cars gradually entering the automotive market and predicted to dominate the market in the near future due to the clamour for 'greener' energy,materials engineers have to stand up to this huge demand[14].

e. Not all metals of high melting points can be successfully sintered [11]. Examples are alloys that have aluminium and magnesium which begin to decompose at their melting temperatures (much below the melting temperature of the alloy). Thus, there is the need to design a successful sintering process for them and save energy used in casting them.

## VI. Conclusion

An overview of the state of the art and applications of sintered metals has been presented. A brief look at the history of sintered metals shows that full-scale sintering of metals commenced in the mid-20th century. Since then, it has grown very rapidly and finds applications in many areas today including automotive and general machinery, medicine and other applications. Hence, the present state of the art regarding sintered metals is that they have a huge indispensable role in materials selection in both new and old areas of applications. There are also rooms, which have been outlined, for future developments and more innovation in this area of metallurgy to overcome its present challenges and meet predicted increase in their demand in a number of applications. Metallic sintering, thus, is a good area of research for materials engineers.

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