Fatigue of Sintered Materials

Fatigue of Sintered Materials:

Theory and Application

By

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Author

FOREWORD

The technical systems' development process is defined relatively precisely and reasonably well supported with modern computer tools. Numerous commercial computer aids or specially developed computer tools are relying mostly on graphic presentation, simulations, engineering analysis (i.e. the Finite Element Method) and animations of future technical system performance in the virtual environment. In the embodiment phase, the designer has to take decisions, influenced by various parameters, according to the available data. One of the crucial decisions is material selection, conditioned by several criteria, among which the proposed project will focus on function, technical features and shape of the developing product or technical system. Other criteria, like serviceability, technical feasibility and economic justification, are going to be considered accordingly. Despite the potential of the already mentioned computer tools, a designer has to evaluate the information gathered from these aids, seek interdependences and, finally, choose the optimum from the broad list of materials. Powder materials will be outlined here, as they are used frequently in technical praxis. On the other hand, there is a lack of relevant data and knowledge for successful selection between them. Consequentially, the designer has to master all influential parameters, their overlapping or contradictions, and, above all, he or she has to know the materials available on the market. A designer's right/wrong decision influences a product's applicability severely in praxis, its technical feasibility, life time, economic justification and recycling possibilities, along with its environmental impact. Thus, numerous experts from various fields usually need to contribute their expertise to reach the final decision, which is often quite difficult, as opinions may be contradictive. In addition, sustainability has to be considered as well. Sometimes, an appropriate intelligent system may support the selection of a suitable powder material according to the function, technical features and design criteria. Such a system may be able to support the designer in the decision-making process, whilst selecting the most appropriate powder material for the product or technical system.

Due to low price, low waste, tight tolerances and evermore improving mechanical properties, Powder Metallurgy (PM) is becoming an interesting alternative mass production process for the future. Especially, the automotive industry has been using this technology to produce non-vital parts. Literature research on this field however concludes that sintered parts will enter the industry as vital automotive parts, such as transmission gears and connecting rods. In-depth chemical analysis, differential scanning calorimetry and thermos-gravimetric analysis have given an important understanding of sintering conditions and the diffusion process between powder particles.

This book by S. Glodež is one of the first Slovenian monographs in international space on the above-discussed subject. It is based mainly on the results obtained by the author and his collaborators during their original research, and concerns the problems of fatigue and fracture mechanics of machine parts and structural components.

Maribor, March 2021
Author

CHAPTER 1

INTRODUCTION

Powder Metallurgy (PM) is a general term which represents all techniques to produce solid-metal-based products from powders [1.1]. This involves powder production and its treatment, one or more consolidation steps involving application of appropriate pressure and temperature, and a multitude of additionally (secondary) treatments, which can be similar to those applied to the wrought metallic components. The world-wide popularity of PM-technologies lies in its ability to manufacture complicated products to exact dimensions, at very high rates and economical prices. However, this technology also has some weaknesses, which are mainly related to the high tooling cost and strength characteristics of PM-products. The main advantages and disadvantages of PM-products are summarised in Table 1.1 [1.2, 1.3]:

Table 1.1: The main advantages and disadvantages of PM-products

Advantages	Disadvantages
• The PM-parts can be produced clean and ready for use. • Close dimensional tolerance can be achieved. • The machining operation can be reduced, or almost eliminated. • The material wastage is small and can be neglected. • Metal powders can be mixed in any proportion. • A high production rate can be achieved. • Composition of structure (porosity, density, etc.) can be controlled easily. • Production of self-lubricated parts is possible.	• The high cost of metal powders if compared to the cost of raw material for casting or forging. • The high cost of tooling and equipment (especially when production volumes are small). • PM-parts generally have lower ductility and strength than those produced by forging, casting or machining. • Uniformly high – density products are difficult to produce. • Large parts are difficult to produce by the PM process due to the large pressure required. • Dimensional changes may appear during sintering.

1.1 The basic process of PM-technology

The two basic elements for manufacturing a sintered component are metallic powder and tooling. Having them, the basic process to follow for producing a sintered component consists of three operations, i.e., powder mixing, compacting, and sintering. The basic principle of manufacturing of sintered components is shown schematically in Figure 1.1.

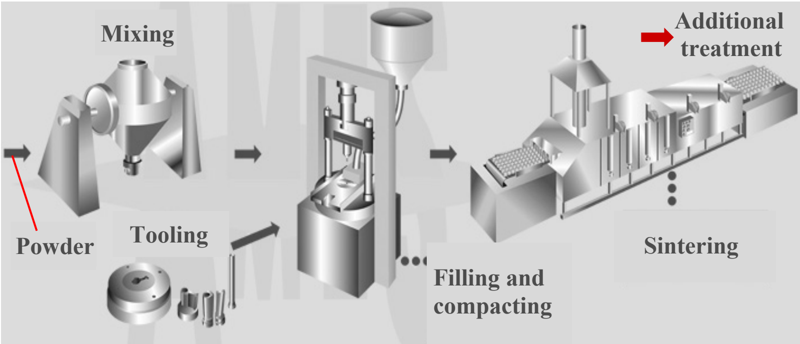


Figure 1.1: Basic principle of manufacturing of sintered components [1.4]

1.1.1 Powder (Raw material)

The raw material of a sintered component is always a metallic powder. Metal powder can be of pure metal (iron, copper, aluminium, etc.), or alloyed powder (bronze, brass, steel, etc.). The material characteristics to be achieved determine the powder's chemical composition.

The production of powders for PM-products can be divided into *mechanical* and *chemical* methods. Here, the final properties and the price of the powder are strongly dependent on the raw-material cost, the production method (large scale vs. small scale), particle shape, size and distribution, impurities, and oxygen sensitivity [1.1, 1.5].

The mechanical methods to produce metal powder are generally divided into (i) Disintegration without phase change and (ii) Disintegration with phase change. The disintegration without phase change is one of the easiest ways to produce powder from solids, where machining techniques such as milling or turning are usually used for that purpose. However, this method is quite expensive, its productivity is relatively low and the danger of contamination is high. For those reasons, it is applied only for special purposes. On the other hand, the disintegration with phase change is the way to produce powder from liquids (water, oil, gases), usually by using the atomisation process. This method is the most modern and productive way to obtain metal powders for PM-production. Namely, most worldwide shipments of iron and steel powders are produced by the water-atomisation technique.

The chemical methods to produce metal powder are generally divided into the following procedures [1.1]:

- *Reduction with solids*. The classical method of metal powder production using ore reduction. The most pronounced feature of this powder is the internal porosity of the particles (sponge iron powder).
- *Reduction with gases*. For the reduction of ores where the final carbon content should be extremely low. Here, reduction by hydrogen is the standard process for the production of tungsten and molybdenum from WO_3 and MoO_3.
- *Electrochemical reduction*. The production by electrolysis from aqueous solutions is applicable for Copper, Iron, Nickel, and Cobalt, and, due to hydrogen overvoltage, also for Chrome and Manganese. The particle size, size distribution, and shape are determined by the electrical current density, the temperature, concentration, acidity, and the bath movement.
- *Decomposition of gases*. The carbonyl method is used mainly to produce fine Iron and Nickel powders. The powders have very low contents of metallic impurities. Although the process is energy consuming, it is the main production method for Nickel and Iron powder.
- *Reaction with solids (Carbides)*. Carbides, as the major raw material for cemented carbides, are usually produced by reaction with carbon (soot). In this way, WC is produced by intense mixing of tungsten powder with the desired particle size and carbon, and subsequent reactive annealling in hydrogen in graphite tube furnaces. TiC, NbC and TaC are produced by direct reduction and carburisation from their oxides (TiO_2, Ta_2O_5, Nb_2O_3) in a vacuum.

The different applications for metal powders require the appropriate powder characterisation regarding their physical (size, shape and distribution of powder particles), chemical (chemical composition, degree of purity), and technological (flow rate, apparent density, compressibility, green strength) properties.

1.1.2 Mixing and blending

The majority of powders are mixed with other powders or different alloying elements (such as Graphite, Nickel, Copper, etc.), binders and lubricants (the addition of binders and lubricants is necessary to provide the desired compaction properties), to achieve the desired characteristics in the finished product. The result is a powder mixture with a homogeneous additive distribution, which is ensured through the strict dosing and control processes, and it is of critical importance in order to achieve the appropriate physical, chemical and technological characteristics of the material. The time for mixing and blending may vary from a few minutes to several days (depending upon results desired), and can be done in either wet or dry conditions.

1.1.3 Tooling

The powder mixture is compacted inside the tooling, which has the negative shape of the final part. The tool is an element of a very high precision and high durability. Tooling assembly and maintenance is usually carried out by means of SMED (Single Minute Exchange of Dies) techniques.

1.1.4 Filling and compacting

The powder mixture is filled into the tool cavity of a mixer by gravity, and a uniaxial pressure within 40 to 1650 MPa (see Table 1.2) is applied onto it, depending on the final density to be achieved. Here, the mechanical, hydraulic or pneumatic presses are used for that purpose. The compacted part is ejected from the tooling, and the result is a "green part", which has a certain mechanical strength and can be handled. The compacting process is usually assured statistically by SPC (Statistical Process Control) controls of the unique characteristics of a part.

Table 1.2: Typical compacting pressures for various applications [1.2]

Application	Compaction pressure [MPa]
Porous metals and filters	40 – 70
Refractory metals and carbides	70 – 200
Porous bearings	140 – 350
Steel parts (medium density)	270 – 690
Cu- and Al-parts (high density)	250 – 275
Steel parts (high density)	690 – 1650

Figure 1.2 shows the typical compaction sequence for a single-level part during the filling and compacting process. Because powder does not flow like liquid, it is simply compressed until an equal force is reached acting in the opposite direction. This opposing force consists of the resistance by the bottom punch, and friction between the particles and die surface.

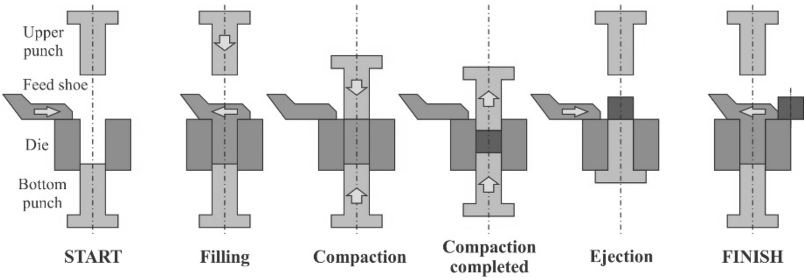


Figure 1.2: Typical compaction sequence for a single-level part [1.2]

When the pressure is applied by only one punch (as already presented in Figure 1.2), the maximum density occurs right below the punch surface and decreases away from the punch. The heterogeneous density actually appears due to friction between the powder particles and friction between the powder and the die walls. This can be avoided if the compacting pressure is applied to the powder evenly from all directions (isostatic pressure [1.6]), which is achieved by placing the powder in a closed flexible mould and introducing the mould in a fluid (liquid or gas) that is pressurised afterwards. In the case of Cold Isostatic Pressing (CIP), the powder is poured into a flexible mould at room temperature and compacting pressure up to 1500 MPa (the pressures used in practice are commonly around 200–600 MPa [1.7]). CIP has become an essential process step for the production of certain PM materials or products: Mo and W (e.g., in arc furnace melting electrodes), hard metal parts (e.g., rollers and dies), high-speed steel products, long thin-walled cylinders, etc. On the other hand, Hot Isostatic Pressing (HIP) is used to densify powders at high pressure and temperatures from 900 °C to 1,250 °C, for example for steels and super-alloys [1.8]. The HIP- process provides improved stability and mechanical properties of solid parts due to the fine and homogeneous isotropic microstructure. Because of its production costs, HIP finds many applications in the production of special PM materials, such as high-speed steels, super-alloys, and titanium alloys. Owing to the properties that can be achieved, many applications can also be found in the automotive and aerospace industries (structure and engine parts), aggressive environments, etc.

1.1.5 Sintering

The green compact produced by compressing (see previous Section), is not very strong and can't be used as a final product. For that reason, sintering is a reasonable production step, which follows after the finishing of compacting stage. According to the ISO definition [1.9], "*Sintering is the thermal treatment of a powder or compact at a temperature below the melting point of the main constituent, for the purpose of increasing its strength by bonding together of the particles*". Following this definition, sintering is a thermal cycle, consisting of heating the compacted part during a given time at lower temperature than the base metal melting point (the sintering temperature is generally about 70 to 90 percent of the melting temperature of the metal powder). The high temperature leads to welding of particles between them, and to the alloying elements by means of a solid-state diffusion mechanism. This process provides strength to the green compact and converts it into a final product.

Sintering can be performed in different variants [1.10–1.12]: Solid phase, activated, liquid phase, reactive, etc. The most straightforward variant of sintering is solid-phase sintering of single component systems, which can be divided into the three main stages (see Figure 1.3). At the beginning, the particles of the pressed (green) part meet at highly deformed pressing contacts (Figure 1.3*a*). In the early stage of sintering, metallic interparticle contacts are formed and grow, but the interparticle porosity is still interconnected and open (Figure 1.3*b*). In the next stage, the pores become closed and isolated from one another (Figure 1.3*c*). Finally, any remaining porosity decreases slowly and grain coarsening occurs [1.13].

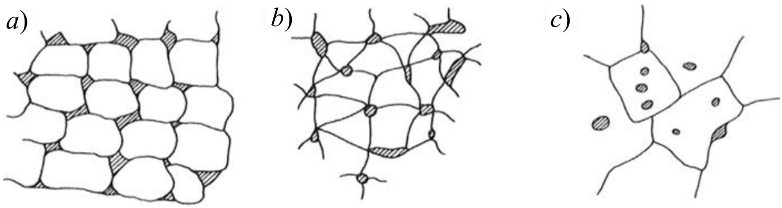


Figure 1.3: Main phases of sintering [1.1]
a) Green state, *b*) Open porosity, *c*) Closed porosity

Sintering is generally carried out in a controlled atmosphere (i.e. a vacuum furnace) to prevent or reduce oxidation of the large number of metal particles. Liquid Phase Sintering (LPS) is also used in some cases, and is carried out at a temperature at which a liquid phase exists.

1.1.6 Additional treatment

Additional treatments (applications) represent complementary operations on a sintered component which allow improvement of one or more characteristics not directly achievable from the basic PM-process. For instance, these additional operations may be used to reproduce complex shapes, achieve closer tolerances, improve mechanical properties, or protect against corrosion. Although some additional costs appear using these operations, the final products are often still economical compared to those from competing technologies. A number of finishing operations (sizing, coining, porosity impregnation, plating/coating, machining, deburring and cleaning, heat treatment, surface densification, joining, etc.) are known to improve specific properties of sintered products [1.1, 1.4, 1.14].

Sizing is a post sintering operation to correct size, distortion and other geometrical defects of a sintered part, or to improve (reduce) surface roughness. The process consists of compacting the sintered part into a die of smaller dimensions, which has the symmetrically opposite shape of the part. The tolerances and properties achievable after sizing depend on the material (the tolerance class up to IT 5 is reachable [1.15]).

Coining is a repressing operation which produces the same results as the sizing. However, coining additionally improves the density, hardness and strength of the sintered part.

Porosity impregnation consists of filling open porosity (pores) with various substances. If the substance used is oil, it can act as a lubricant of the sintered part (i.e. self-lubricated bearing bushes). Plastic or resin impregnation provides sealing (this operation is quite common as preparation of the sintered parts before plating/coating). Sealing the open porosity also provides some increase in mechanical properties, improves pressure-tightness, and has a positive effect on machinability. Furthermore, copper impregnation (infiltration) consists of sintering the part together with a pressed copper plate on it. Copper is molten during sintering, and becomes infiltrated inside the pores by means of capillarity. This procedure is often used to increase the mechanical strength and toughness of low alloyed sintered steels.

Plating /coating is a material deposition on the component surface, which modifies the surface properties without changing the base metal chemical composition. The final result is improved wear resistance and corrosion protection [1.16]. *Plating* is performed on sintered parts in the same way as in wrought or cast materials, where Cu, Ni, Cd, Zn, Cr and other metals are deposited galvanically on the surface. However, in PM parts, the surface pores must be sealed before plating using an appropriate impregnation process. *Coating* is applied to a large percentage of hard metal inserts. Here, the Chemical Vapour Deposition (CVD) and the Physical Vapour Deposition (PVD) processes are usually used to deposit ceramic layers of TiC, TiN, Al2O3, TiAlN, etc. As presented in [1.17, 1.18], the coating performance can be improved by the combination of several thin coating layers (multilayer coatings).

Machining. Sintered components can sometimes be machined when a shape or tolerance not achievable by compacting is required. Sintered parts support all conventional machining operations (turning, milling, drilling, threading, grinding, lapping, reaming, polishing, etc. [1.19). However, the machining parameters for sintered parts are different from those of cast or wrought components, and are dependent on typical PM-properties (density, chemical composition, additives, etc. [1.20]). In general, machining becomes more difficult with higher porosity levels and with heterogeneous microstructures. The machinability of PM parts can be improved by using some additives prior to compaction (Pb, Cu, S, MgS, graphite, etc.). Furthermore, infiltration with low-melting point metals or polymer (porosity impregnation) is a common practice to improve machinability.

Deburring/cleaning. *Deburring* is applied to remove burrs, sharp edges, or surface irregularities resulting from compaction or machining operations. Burrs are removed either in bulk (tumbling, shot blasting, etc.), or on a unit basis (brushing, polishing, electrolytic deburring, etc.). *Cleaning* operations are used to reduce or eliminate the amount of pollutants, solid or liquid, that a part may contain. There are many techniques (ultrasonic cleaning, electrolytic cleaning, etc.) depending on the material, type of pollutant, and required specifications which may be used for that purpose.

Heat treatment involves heating and cooling of the sintered part to modify (improved) it's material properties (tensile strength, fatigue strength, impact toughness, hardness, wear resistance, etc.). The main heat treatments of sintered parts are:

- *Induction hardening* allows performing a heat treatment only in certain areas of the part surface. The depth and hardness of the hardened layer can be controlled by appropriate heating and quenching parameters.
- *Case hardening* is a process for increasing surface wear resistance and fatigue strength. The chemical composition of the surface is modified by carburising (local diffusion of carbon) or nitriding (local diffusion of nitrogen), and the sintered part is subsequently quenched.

Surface densification is a mechanical process to increase the density of near-surface layers of the sintered part. The process is based on the controlled localised plastic deformations which create compressive residual stresses in the surface layers, and, consequently, improve the fatigue properties of the sintered part significantly [1.21]. The main surface densification procedures of sintered parts are:

- *Shot peening* is a cold working process in which small spherical particles from metal or ceramic are impacting the surface with enough energy to cause plastic deformation, and, consequently, induce compressive residual stresses in the surface layer of the treated component. Shot peening has an additional effect, because plastic deformation closes smaller pores and reduces the size of larger pores on the surface [1.22].
- *Surface cold rolling* is a cold working process in which the worked piece (sintered part) and rolling toll are meshing (rolling between each other) to remove a controlled amount of excess material on the surface of the sintered part. This method is usually used for local densification of sintered bearing races and sintered gears, to improve wear and pitting resistance [1.23, 1.24].

Joining. Sintered parts are susceptible to being joined to other sintered parts or to components made from other technologies [1.4]. Typical joining techniques are welding, brazing, sinter-bonding, fitting, sticking, riveting, over-moulding, etc.

1.2 PM-products

The capital goods industry (the automotive, electrical appliances, hand-tool industries and other high-volume industrial segments) is a major consumer of sintered parts. As a reference, each car uses between 10 and 15 kg of sintered parts (about 600 sintered components with an average weight of 20 grams). A wide range of materials, shapes, finishes, treatments and coatings can be used to produce PM-parts with a high accuracy and performance. Their mechanical properties are, in some cases, comparable to those of wrought or cast products [1.4].

Sintering is used to make a great number of different structural products: High-strength and high-precision components, tribological parts (oil-impregnated bearings), electrical parts (contact elements for Low- and High-Voltage switchers) and magnetic parts (soft-magnetic components). Additional opportunities of PM products are hardphase-based materials, refractory metals, PM-superalloys, etc. [1.25].

Structural parts made of low-alloyed steel represent a large portion of PM-products. Many of these advanced structural parts need the appropriate secondary operation (see Section 1.1.6) to improve their strength characteristics [1.26]. Some typical examples of PM-structural parts are shown in Figure 1.4.

a)

b)

c)

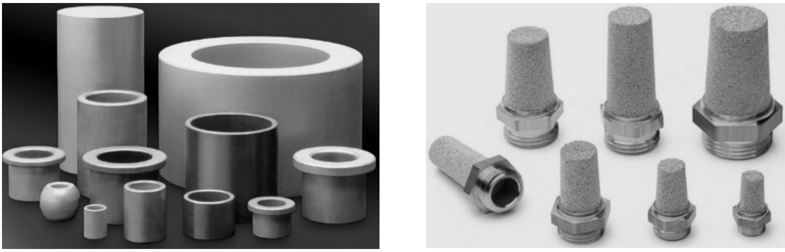
d)

Figure 1.4: Examples of PM-structural parts (Ames [1.4], Capstan [1.27],) *a*) Different types of gears, *b*) Components of oil-pumps *c*) Gears and toothed parts of sundry shapes, *d*) Components for steering applications

If corrosion resistance is required, PM-structural parts are usually produced from austenitic, martensitic, or duplex stainless steels [1.1]. Here, the Metal Injection Moulding (MIM) has extended the application of corrosion-resistant steels to small and complex parts for automotive and medical applications. The main difference of these products, apart from their complex shape, is the almost full density and closed porosity, which is reached by the MIM-process using extremely fine powders.

In some special applications, PM-technology can also be used to produce tool steel parts with complex shape in high quantities (cold work tools for pressing dies and punches, hot work tools for injection moulding inserts, high-speed steels for the highest operating temperatures, etc. [1.28]). Here, the conventional pressing is combined with the supersolidus liquid phase sintering in a vacuum [129].

PM-technology is also suitable for producing different tribological parts, where the Copper (Cu) is often used as the main alloying element in the raw material (powder). The major Cu alloys produced by PM are bronze (Cu-Sn), brass (Cu-Zn), and Ni–Ag alloys. A key feature of using PM for the production of tribological parts (i.e. self-lubricated bearings, Figure 1.5*a*) is the ability of this technique to produce porous metallic parts in which the level of porosity is controlled, as well as the shape and size distribution of the pores. A self-lubricating sintered bearing is a metallic component with high porosity (usually between 20-25%), impregnated in a lubricant oil. The oil contained in the porosity provides a constant lubrication between bearing and shaft, so the system does not need any additional external lubricant. A self-lubricating sintered sliding bearing can operate under hydrodynamic lubrication conditions, resulting in a very low friction coefficient. Another example of the use of PM-structural parts with controlled porosity are filters (Figure 1.5*b*). Typical application areas are the chemical industry (water purification, nuclear installations, heat exchangers, general drying, etc.), the food industry (gasification of liquids and spirits, liquefaction, packaging manufacture, etc.), household appliances (boilers, water heaters, gas burners, etc.).



a) *b*)

Figure 1.5: Sintered parts with controlled porosity (Ames [1.4])
a) Self-lubricated bearings, *b*) Filters

The use of PM-products in the electro industry is related mostly to the contact parts for Low- and High-Voltage switchers. The base material for Low-Voltage switching is silver, due to its high electrical conductivity and its chemical stability against the surrounding atmosphere (air) [1.30]. Silver-based composite materials produced by PM-technology are used to withstand the mechanical loads during switching to reach sufficient wear resistance and suppress the welding tendency [1.1]. The High-Voltage switches are used in the medium voltage range up to 40 kV. These kinds of switches are usually made of Cu-Cr alloys.

Sintered soft magnetic parts are typical PM-products to guide or amplify a magnetic field. Their function in an electromagnetic circuit is to transform an electrical signal into motion or to transform motion into an electrical signal, based on their ability to be magnetised and demagnetised easily and quickly when a magnetic field is applied or removed. Some typical examples are shown in Figure 1.6.

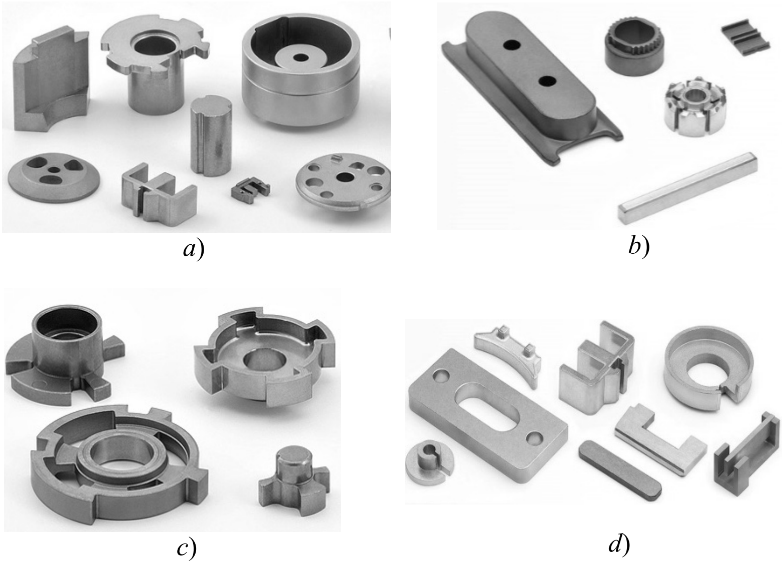


Figure 1.6: Typical examples of soft-magnetic sintered parts (Ames [1.4])
a) Actuators (winding cores, armatures, stators, rotors, housings, etc.), *b*) Electrical machine components (pole pieces, winding cores, contactors, switches, etc.),
c) Pulse sensors (ABS brakes, vehicle engines, camshafts, crankshafts, etc.)
d) High-sensitivity detectors (when a fast response is required)

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CHAPTER 2

FATIGUE – THEORETICAL BACKGROUND

Fatigue of engineering components and structures is a localised damage process produced by cyclic loading. In general, it has been observed that the fatigue process involves the following stages [2.1–2.8]: (1) Crack nucleation; (2) Short crack growth; (3) Long crack growth; and (4) Final fracture. In engineering applications, the first two stages (crack nucleation and short crack growth) are usually termed as "*crack initiation period* N_i", while the last two stages (long crack growth and final fracture) are characterised as "*crack propagation period* N_p". The complete fatigue life of an analysed engineering component can then be determined from the number of stress cycles N_i required for fatigue crack initiation, and the number of stress cycles N_p required for a crack to propagate from the initial to the critical crack length, when the final failure can be expected to occur:

$$N = N_{\mathrm{i}} + N_{\mathrm{p}} \tag{2.1}$$

An exact definition of the transition period from the initiation of an "engineering" crack to its propagation is usually not possible. However, for engineering components made of steels the size of initial crack a_{i} is of the order of a few crystal grains of the material. This crack size usually ranges from about 0.1 to 1.0 mm. According to Dowling [2.4], the crack initiation size can also be estimated by the following equations:

$$a_i \approx \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta S_e}\right)^2 \qquad \text{smooth specimen} \tag{2.2}$$

$$a_i \approx (0.1 \ldots 0.2) \cdot \rho \qquad \text{notched specimen} \tag{2.3}$$

where ΔS_e is the stress range at the fatigue limit, ΔK_{th} is the threshold intensity factor range, and ρ is the notch-tip radius.

In general, four fatigue design criteria can be used for dimensioning structural elements subjected to cyclic loading [2.2]:

- Infinite-Life Design,
- Safe-Life Design,
- Fail-Safe Design,
- Damage-Tolerant Design.

Infinite-Life Design

Infinite-Life Design is the oldest fatigue design criterion, which is based on the *S–N* curve, with the assumption that the engineering component is going to reach "infinite" life (usually several millions of cycles). According to this criterion, the stresses are in the elastic area, and should not exceed the fatigue limit of the material.

This criterion is combined exclusively with the Stress-life approach, and is suitable for dimensioning dynamically loaded machine parts or structures which are, in the framework of their fatigue life, actually exposed to millions of cycles (engine valve springs, axes and bearings of railway wagons, shafts and gears of high stages in change-speed gear drives, etc.). However, most engineering components undergo significant variable amplitude loading, and the pertinent fatigue limit is difficult to obtain. In addition, this criterion may not be economical in many design situations where the expected fatigue life is shorter (shafts and gears of low stages in change-speed gear drives, certain parts in the aircraft industry, etc.).

Safe-Life Design

Safe-Life Design is a fatigue design criterion where the engineering component is designed for a finite life, which is often known in advance. This criterion should include a margin for the scatter of fatigue results and for other unknown factors (surface roughness, notch effect, residual stresses, temperature, corrosion, etc.). The dimensioning process may be based on the Stress-life approach if stresses are in the elastic area, or on the Strain-life approach if plastic deformation occurs in the critical cross-section of the treated component.

The Safe-Life Design criterion is suitable for dimensioning dynamically loaded machine parts or structures with an expected specific finite life (reverse gears in car drives, pressure vessels design, jet engine design, etc.).

Fail-Safe Design

Fail-Safe Design is a fatigue design criterion which assumes that some initial cracks may appear in individual parts of engineering structures, but they are not critical and do not lead to a catastrophic failure of the structure. This fatigue design criterion was developed in the aircraft industry. Namely, aircraft engineers could not tolerate the added weight required by large safety factors, or the danger to life created by small safety factors, or the high cost of the safe-life design. In that respect, the fail-safe design is based on the requirement that the system does not fail if one part fails. This principle recognises that fatigue cracks may occur, and structures are arranged so that cracks will not lead to failure of the structure before they are detected and repaired. In that respect, inspection intervals should be defined exactly when using the fail-safe design criterion. Although this approach was originally applied mainly to aircraft structures (fuselages, wings), it is now used in many other applications.

Damage-Tolerant Design

The *Damage-Tolerant Design* criterion is actually a refinement of the Fail-Safe Design criterion. It is based on the assumption that initial defects exist in engineering structures, which were caused either by mechanical and thermal treatment of components during the manufacturing process, or by fatigue. A fracture mechanics analysis can then be performed, in order to determine whether such defects will grow large enough to produce failures before they are detected by periodic inspection.

In recent decades, several nondestructive inspection methods have been developed to detect possible defects (cracks) in a treated engineering component. If a crack is detected, the residual strength of the treated component should be obtained using the fracture mechanics theory. As a crack growth under cyclic loading, the residual strength decreases up to the critical crack length, when final failure (fracture) occurs. If there is no crack, the residual strength is equal to the ultimate tensile strength or yield stress of the material. Apart from those described above, some other influencing parameters, such as environmental conditions, load history, statistical evaluation, etc., should also be incorporated into this methodology.

The damage-tolerant design criterion is often used when evaluating the residual strength of complex and expensive engineering components, which should be retired from service because they have reached their designed safe-life service life, based upon analytical and experimental results. However, it has often been established that such components could have significant additional service life.

In a combination of the four fatigue design criteria as described above, three main fatigue design approaches can be used when dimensioning the cyclic loaded machine parts or structures [2.2]:

- Stress-life approach ($S - N$),
- Strain-life approach ($\varepsilon - N$),
- Fatigue crack growth approach (da/dN–ΔK).

2.1 Stress-life approach

The *Stress–life approach* is the oldest method for dimensioning dynamically loaded structural components. This approach is based on the *S–N* curve that is commonly plotted in terms of stress amplitude σ_a versus number of loading cycles to failure N, usually in log–log scales. The most basic *S–N* curve is considered to be the one for zero mean stress $\sigma_m = 0$, which corresponds to the stress ratio $R = \sigma_{min}/\sigma_{max} = -1$ (see Figure 2.1).

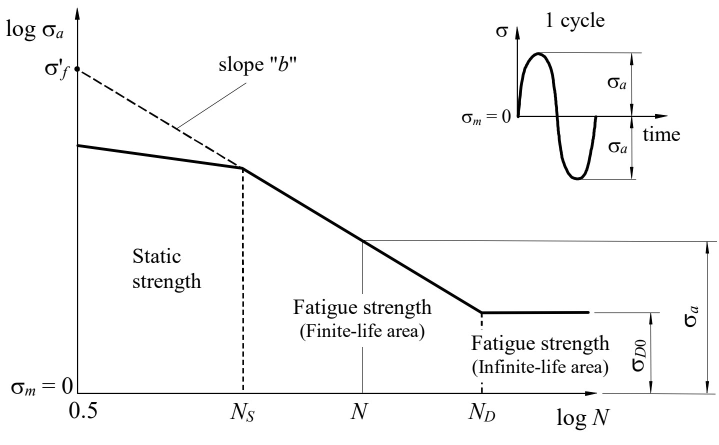

Figure 2.1: *S–N* curve in a log–log scale

For most engineering materials, a distinct dynamic stress level exists below which fatigue failure does not occur under ordinary loading conditions. In this area (i.e. the *Infinite-life area*) the *S–N* curve becomes flat and corresponds to the *fatigue limit* σ_{D0}. The belonging number of loading cycles N_D (knee of the *S–N* curve) is usually between 10^6 and 10^7 for most engineering materials. In the *Finite-life area*, the term *fatigue strength* (or dynamic strength) is used to specify a stress amplitude σ_a from an *S–N* curve