Quality reinforcement, exploratory research and tendencies in sintering process manufacturing

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Abstract. The present work has the scope to highlight the connections of the systems involved in different process like additive manufacturing process, like sintering and their importance for design and development of new candidate materials. Aluminum alloys and composites are used worldwide, from automotive to aerospace and marine. Their significant proprieties, with complex internal structure are difficult to produce using conventional processes. Additive manufacturing has becoming very popular nowadays. Compared to conventional procedure with this solution presented, complex shapes, infill densities and lead times are not any longer problems. The study relays it can inspire newcomers to the field to broaden their view within new technologies, new effects on the materials and on fragmentated performance of the products. The aim is to fulfill the gaps between customer achievement and product quality in mostly all processes approach and their practice currently, that causes problems like ambiguity of results and difficulty to handle special products.

1. Introduction
The process of sintering it is a process that can assure a very good surface finish and an outstanding dimensional accuracy. The porosity inherent by this can be used for sensitive components like filters, bearings, eccentrics. One of benefits of this process it is that by this method can be produced with refractory materials that usually are impossible to shape using other procedures with materials of lower melting points. For this, are considered categories of parts, haven its own unique considerations: gears, cams, assemblies, bearings. There are 2 important types of process relevant for this technology: the laser sintering that is referring to the procedure by solidifying power like materials layer by layer that is showing the surface of a powder platform with a laser or another energy source and the direct metal laser sintering that is using a metal powder so that metal components are made direct in the tools. The last process will be the one discussed along the paper.

2. Sintering technology
The sintering is a process that can allow 2 different types of material, dense and detached, that it is converted into a compact and firm product. What is specific about this process is that allows to shape parts using this method with materials than can go below their melting points. Through this procedure, the powder particles are encompassed, joining itself, which creates good surface finish, dimensional accuracy and a mechanical toughness for the whole product.

  › Pro arguments
    › Almost final shape components ➔ few/no machining needed
2.1. Process of sintering

The process itself of producing the parts by this way can have different steps, depending on the usage of the parts and the necessities from the design stages. Usually the parts made from this process fitting to be used in case of supplying balls and needle bearing when necessary, are used mostly because there are cheaper and technical precise by decreasing noise and prevention for the formation of rust and corrosion.

In the initial phase of the process, by sintering the surface, the energy of the powder used is reduced, a mass transfer also is activated using heat and is occurring in the end the particles bonding through heat for making a product with high quality properties.

What makes difference between sintering and another process from the additive material procedures, are the benefits that the shrinkage is less than 5% instead of normal injection molding machines that is around 12~25%. [1] It is known that in the atmosphere of the sintering process the metals build oxides on surface at high temperatures and that is why an intensive control of the process is necessary. Additionally, this could be avoided if the metal powder in the incoming inspection would include analyses of the powder chemistry, particle size and distribution, flow rate checks, density checks, microscopic evaluations, compressibility and compatibility. [2] The porous parts are much more sensitive for oxidation than solid parts and is affecting the growth of sinter necks and bridges between the particles. In the solid state of sintering, some alloying elements might melt during process. The diffusion of alloying element into iron particle can cause a part of inflation instead of shrinkage. The best example is copper usage.

2.2. Lessons learned - sintering process

The limits on tolerances are influenced by orientation of the dimension to the pressing direction, size, and component complexity, material used, variations in the process and secondary operations. [3] So, the following table (Table 1.) is containing some typical tolerances for a ferrous product component that is usually measured up to 100 mm in diameter and 25 mm thick.

The measurements were performed with a 3d measuring machine and was determined on a batch of parts with different geometries and measurement. The results are that the units are very thin, and the width is very small. For this, the walls need to have very thin sides tooling, then can expand the usability of creating tool failures (needs to be less than 2 mm). If is needed a knife-edge and vitally for the product, the component will have an increase chance to be crack in the future. The rounded extremities will permit a better flow of the powder course and the lifetime of the tooling will be longer. The parts can be joined by conventional procedures but is not recommended to use the development of feather edges and the proper example would be the piston-shaft mechanics. In this case, the dies and the tooling used are very brittle and keeping the maintenance in place will be difficult and, in the end, will create failures and defects. The recommendation of the specialists is to used radii and not very tight and sharps corners even from the designing of the dies. All-sharp edges, like mentioned until now, should be designed and replaced by radiusing. A connection made by radius and not by edges will not only prolong the life of the tooling but also will secure the part itself.
Table 1. Results taken after a batch of 50 parts with different geometries were measured

| Pressed and Sintered Tolerances          | Result obtained by practical experiment | Result that could be possible to be obtained |
|-----------------------------------------|----------------------------------------|-------------------------------------------|
|                                         | mm (in.)                               | mm (in.)                                 |
| Length (+/-)                            | 0.190 0.005                             | 0.130 0.005                              |
| Inside diameter (+/-)                   | 0.100 0.004                             | 0.005 0.002                              |
| Outside diameter (+/-)                  | 0.100 0.004                             | 0.005 0.002                              |
| Concentricity                          | 0.150 0.006                             | 0.100 0.004                              |
| Flatness on ends                       | 0.130 0.005                             | 0.100 0.004                              |
| Parallelism of ends                    | 0.130 0.005                             | 0.100 0.004                              |

For designing the holes and the wideness of the walls the best will be to execute holes in the manner that will reduce the total weight of the part. Like side effects would be a less quantity of powder and the pressing surface will be smaller. By this, the cost will be reduced only by making the round holes instead of polygonal holes with the simple reason behind that the tool itself it is easier to be made. For manufacturing gear teeth, it is recommended to have a module less than 0.5 mm, that additionally will require mechanical strength and gradually will slow the flow of the powder. The tool will provide smaller radius. The proportionality between diameter and tallness of unsighted holes it is suggested to have diameter and base to the ratio 1:2. The parts that are smaller in depth and wide in surface can create problems in the manufacturing problems because having such a vast density will create variations and because of the thickness that are more open to cracks during process. Groves, undermine cuts and fractious-holes usually cannot be made in the pressing processed and they are made after by machining, sintering or sizing. It would be great if from the beginning of the projects it would be avoided pointed out deep splines, that are necessary to the construction of dies with significant diminution and because of that the unsteady sections. The procedure for this type of teeth mentioned until now (long and tight) will make harder the outflow of the powder mix in the die cavities and by this usage of the die, they will become especially sensitive. One of the advices regarding using several punches, where the widths of the sequence granted it, it is recommended to used. However, like mentioned until now, even from the beginning in the design phase, must be considered and taken into the account the tooling robustness and stability during process. This is mainly to skip the buckling of strikes during the pressing and squeezing of the raw material. It is desirable a development of the product and of the tool with less punches. If the press machine cannot make more than one lower strike, it should be analyzed the possibility of adopting a shelf die.

Oil immersion for this process it is preferably to be done under vacuum because otherwise will remain on the part and the extra quantity will not be evaporated by the heat. However, the easiest way of impregnating the parts is to immerse them in warm impregnation oil. The part should be left immersed until no further bubbles are observed. Cleanliness and quality of oil in use shall be monitored and controlled. Cleanliness of parts shall be guaranteed after impregnation, and to not be followed by any subsequent process such as centrifugal drying. But, this goal is not always kept. So, it could be faced for example, oily die. The accumulation of fine particles from the powder mix, are gather in oil drop over time. The materials that are usually affected by this, like side effect are: graphite, nickel, manganese sulphide MnS. This can lead to agglomerations in grain structure. This can be avoided usually by maintenance and 5S methodology (work place organization method). [4] The powder it is the engine from the beginning of the project. Rusty iron particles in powder also can create a problem in process. One of the root causes can be storage of powder in open cartridges over long time. The rust (iron oxide) gets reduced during sintering.
3. Particularly case study
In the sintering technologies using the powder compacting process, there are some failures modes that can demonstrate what can go wrong. Discharged cracks, density fluctuation, small layers of laminations, and weak sintering are common types of defects. The carbonization / de-carbonization process can interfere by adding or removing carbon that is causing altered gain structures on surfaces/ grain borders. [5] In the end this is influencing the mechanical proprieties. The contributors on this can be composition of sintering atmosphere and carbon that is evaporated by lubricants in the de-waxing process. Another side effect is the flaky pastry-style structure. The root cause of this is that the catalytic cracking of CO causes segregation of soot(carbon). [6] The sporadic potentially effect during de-waxing can make a volume increase causing cracks before production starts. The main contributors to this are pure and atomized water and metallic bright iron, that is used like lubricant for zinc stearate and additionally there is a sensitive temperature for this material range from 550-600 °C.

![Figure 1. Caption viewed from microscope of a gear](image)

One practical example of this is a crack in the sinter wheel at radius area that was not detected during NDT inspection station. The crack was detected from an investigation which was done on a batch of parts from a supplier and was checked within in the AOI inspection. The result can be seen in Figure 1. The crack occurred around the R-arc, near gauge point with a depth of 2.6 mm and 1/6~1/4 off all teeth. These cracks in the sintered gear wheels can lead to malfunction of gearing due to broken off particles or completely broken off teeth. Root causes for this are: two potential factors at the same time caused by the friction & force for the green crack. The first potential factor could be ejection cycle &wrong deflection compensation (UL2) and the second one could be the worn out of the punch that leaded to the friction increase. (see Figure 2.

The wear of the tooling in this case was accelerated, because uncoated tools should not be used in this step of the process. Also, an agglomeration of dirt (powder and waxes) on the punch can also lead to this higher friction that created the problem in the beginning. [8] For this practical case, only one batch was affected by this problem until was discovered in a proportion of 30%. This can be avoided if the internal traceability of the part is followed and respected FiFo (first in, first out) consequently. Usually this type of failures is controlled by an acoustic resonance test. The crack revelation is discovered by different and several methods, for example, mechanical evidence testing, testing the microstructure of the metals, and nondestructive tests. [9] The list of NDT (Nondestructive test) methods for PM applications is containing electrical resistance proofing, magnetic bridge proofing, magnetic fragment analyze, ultrasonic evidence, gas allowance and permissibility evidence and gamma-ray density assurance, etc. There are several actions that can be implemented to improve and avoid this kind of process. [10] Some actions like the following ones could help: increase maintenance frequency on compacting tools
Figure 2. How the discharge lead to cracked parts

All the parts involved into this correlation process can be seen in the Figure 3. The interdependency of the input, equipment, profile and parameters are explained during the paper and seen in the graph. Any program changes are recommended to be recorded in change’s list during production of each batch and investigate the potential to implement a “machine logic” in Soft- and Hardware at the press, that will limit the parameters setting of the presses for the persons in charge of using this. By the last action a prevention of usage of wrong parameters for compacting can be avoided, like explained up..

Figure 3. Process correlations

The density distribution, gradient and variation within the part, especially parts with multiple steps/levels, for good results needs to be studied and properly controlled as defined in the control plan to avoid ejection crack, stress concentration which may be a fatal flaw in service, like explained in the previous example and to ensure proper performance for the intended application. One effect that should be taken in account is the insufficient sintering period or the insufficient sintering thermal condition that in a diminishing atmosphere and a week lubricant loosen, leads to the reticence of graphite disintegration that can weaken the sintering procedure.

The incorrect drying process can have an influence. In Figure 3 is an overview of the factors that are involved in this one. Out of this, there are some rules like that the drying temperature needs to be used under recommendation and a convection oven must be used to get proper air circulation and together
with an exhausting system, to remove the evaporated solvents. The incomplete drying can have root causes like outgassing during sintering process, not well-done sintering connection and the result are different porosity.

4. Conclusions
The metal powder technology using the process of sintering has the potential to expand a world of discoveries. The intrinsic characteristics of metal powders have the unique possibilities to suit designs that would correspond the actuals necessities of the worldwide automotive production. In the paper there were presented solutions not only for obtaining a better quality of the parts but also only to formalize information that has been already blazed. In the 3rd chapter there are presented some advices and also a particularly example of a defect with corrective actions behind. The strategy used must be followed with discipline and the suspected root causes must be confirmed with an appropriate statistical test, like described in chapter 2. Using this it can be assured that the parts will be produced without problems accomplishing the requirements imposed by the customers.

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