ADVANCES IN STEEL POWDERS FOR HIGH PERFORMANCE PM PARTS

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ABSTRACT

Over the last decades many new powder metallurgy components have been developed and the average growth has been around 6%/year. This is substantially higher than for other technologies such as casting, forging and machining of bar stock. This growth is expected to continue at least at the same pace if not higher. The prime reason for the increased use of PM components is the combination of strength and dimensional tolerances which in this paper is defined as "The Powder Metallurgy Playing Field". Characteristics of different sections of this "playing field" are defined and typical materials representing these fields are presented.

The paper presents four high strength materials and compares mechanical properties and dimensional tolerances of these. The four materials are alloyed with two or more of the alloying elements Cu, Ni, Mo and Cr and the alloying methods are diffusion alloying, pre-alloying respectively combinations thereof.

INTRODUCTION

The two main factors for the increased use of powder metallurgy steels are close dimensional tolerances and high mechanical strength. Many new PM components achieve final geometry without the need of machining and mechanical performance reaches similar level as fully dense wrought steel. These achievements have been possible thanks to new advanced metal powders in combination with compaction tooling, presses and sintering furnaces utilizing the latest modern technology. This paper presents some of the highest performing PM steels, their alloying methods and means to further improve the dimensional tolerances.

PM – A GROWTH TECHNOLOGY

Over the last ten years the powder metallurgy manufacturing method has been established as a high quality technology and the most competitive method for producing complex geometrical parts with weights up to 1 kg and in production series over 100 000 parts/year. The PM technology is superior to casting and forging as it concerns dimensional tolerances and can achieve mechanical properties at the same level as machined components as well as forged.

The graph in Figure 1 schematically presents different manufacturing methods and the range for strength respectively dimensional tolerances achievable. As identified in the graph PM is the preferred technology for components with low to high strength and demand for medium to good dimensional tolerances.

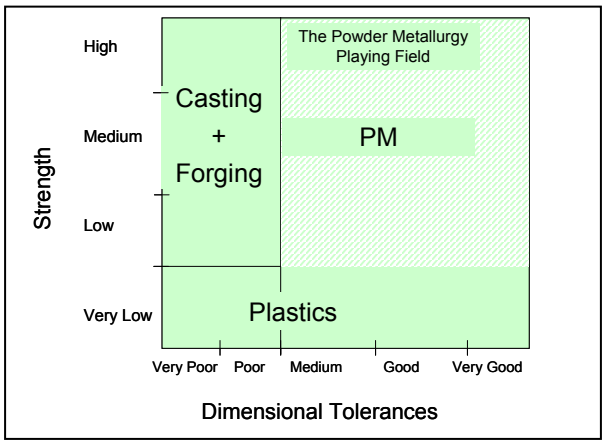


Figure 1: Definition of the "Powder Metallurgy Playing Field" related to mechanical strength and dimensional tolerances

THE POWDER METALLURGY PLAYING FIELD

As shown in Figure 2 the powder metallurgy technology can be divided into sections with different demand on strength and dimensional tolerances. The whole square with low - medium - high strength on one axis and medium- good - very good dimensional tolerances on the other axis can be defined as the "Powder Metallurgy Playing Field". The competitiveness compared to casting, forging etc. improves as both strength and tolerances increase. The strongest competitiveness is the combination of high strength and very good dimensional tolerances up in the right corner of the square.

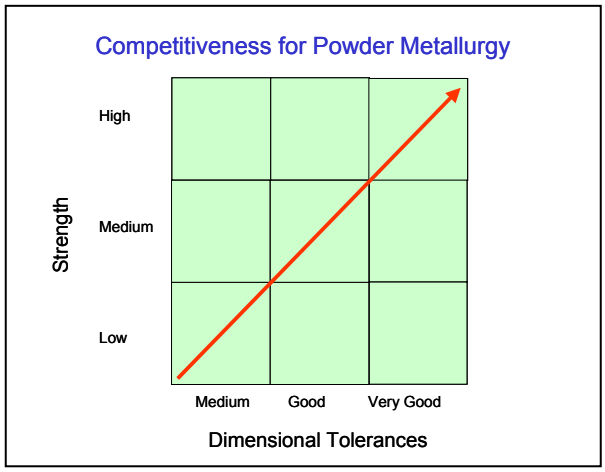


Figure 2: The competitiveness of the "Powder Metallurgy Playing Field" increases with strength and improved dimensional tolerances.

If tolerances are not achieved after processing (or if the shape of the components cannot be achieved during forming) machining must be used. The number of machining steps in combination with "lack" of machinability increases the manufacturing cost as shown in Figure 3. The highest costs will be in the upper left corner of the square because the material is hard and tolerances are poor (medium).

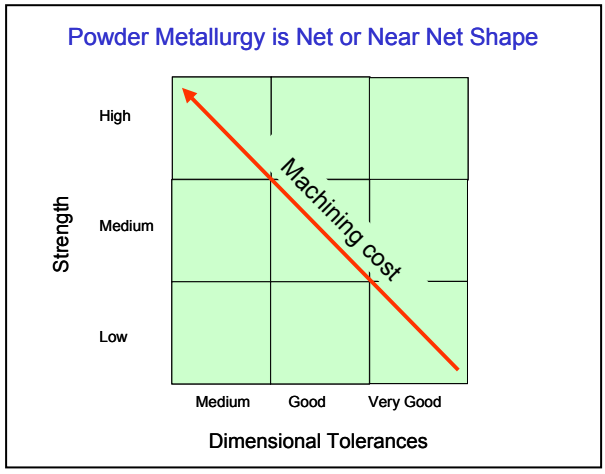


Figure 3: Competitiveness of PM is high if machining costs
are low as compared to other manufacturing technologies

The square for the "Powder Metallurgy Playing Field" can be divided into sections with different characteristics indicating combinations of strength/tolerances with different competitive opportunities. This is shown in Figure 4 and described below.

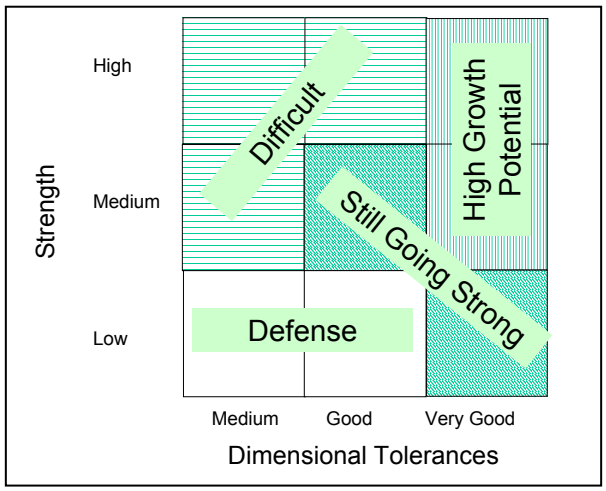


Figure 4: Sections of the "Powder Metallurgy Playing Field"
with different competitiveness

Defense

The lower left corner combines low strength with medium to good tolerances. Many existing PM components fit into this category. Manufacturing costs are low and density is typically below 7.0 g/cm^3 in combination with no or very low amount of alloying addition i.e. copper/carbon. Competing technologies are for example plastic components or stamping of steel sheet. By further cost reductions this "defense section" will continue as an important component category for PM.

Still Going Strong

This area of the "Powder Metallurgy Playing Field" represents components with low strength but very good dimensional tolerances as well as those with medium strength and good tolerances. These sections represent strong areas for powder metallurgy and many new applications are possible. Further needs for very good dimensional tolerances can be achieved with diffusion bonded powders and organically bonded powder mixes as well as with controlled part manufacturing systems.

High Growth Potential

In the long term this section of the "Powder Metallurgy Playing Field" has the highest potential for growth into new applications. It combines medium to high strength with very good dimensional tolerances. The close tolerances prevent or reduce the machinability and thereby avoid high manufacturing costs and the mechanical performance reaches that of cast, forged or machined wrought steels. Typical materials are alloyed with elements having high hardenability effect and components have a density above 7.1 g/cm^3. Close dimensional tolerances are achieved directly after sintering and machining is limited to grinding or similar.

Difficult

This corner of the square is suitable only for niche materials with properties that cannot be achieved with any other manufacturing method. Costs are high due to extensive machining and long production series are normally not feasible.

MATERIAL PLAYERS ON THE POWDER METALLURGY PLAYING FIELD

Most materials used for PM components today would fit into the section "Defense" or "Still Going Strong" whereas many of the newly developed PM applications utilize materials from the section "High Growth Potential". Examples of powders used for those components are shown in Figure 5.

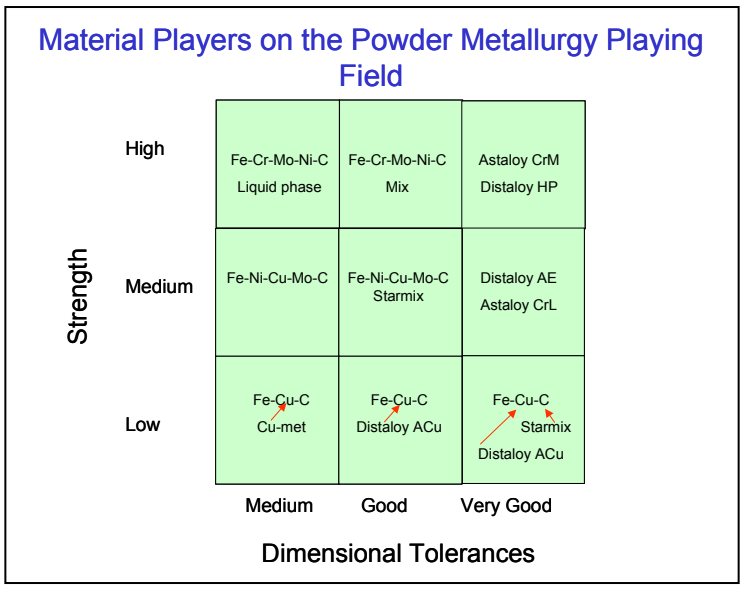


Figure 5: Some PM steels and their position in the "Powder Metallurgy Playing Field"

Typical materials with low strength are alloyed with copper and/or carbon. The tolerances are improved from medium to good by either using diffusion alloyed Cu such as i.e. Distaloy ACu or by bonding using i.e. Starmix powder grades [1-4]. Further improved tolerances are achieved by combining both diffusion bonding and bonding with organic binders. An example of the influence of this step-wise improvement of the tolerances is shown in Figure 6. In this case it was possible to reduce the dimensional scatter to half by utilizing both the diffusion bonding system for copper and by stabilizing the powder mix with organic binders according to the Starmix concept.

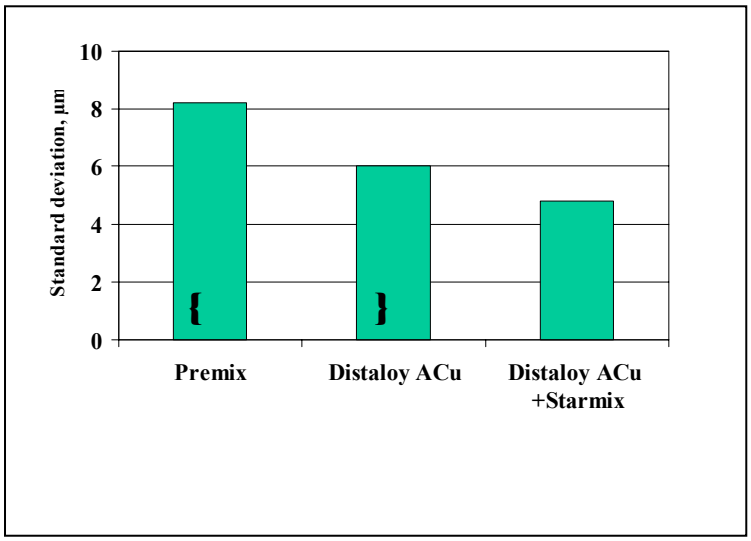


Figure 6: Dimensional tolerances of outer diameter (43 mm) of sintered gears made of Fe + 2%Cu + 0.8%C by **1)** ordinary premix and Cu-met, **2)** Cu added as Distaloy AC and **3)** same as mix 2 but bonded according to Starmix (750 parts/mix type).

Another example to reduce the scatter of the dimensions is shown in Table 1. In this case 160 gears with an outer diameter of 22 mm (12 teeth) was made from two different mixes reaching the same mechanical strength. In one mix based on prealloyed powder Astaloy A, 2% Cu was added in order to achieve the strength level whereas in the other mix based on the prealloyed powder Astaloy CrM strength was reached without the addition of copper. The critical dimension for this gear is distance between the teeth. The data in the table shows that the material based on Astaloy CrM without Cu-addition has closer tolerances both after sintering at 1120°C and 1250°C. It also shows that high temperature sintering does not reduce the dimensional tolerance.

TABLE 1
AVERAGE SCATTER, 6 σ, OF TEETH DISTANCE FOR GEAR WITH OUTER DIAMETER 22 MM, 12 TEETH AND TEETH DISTANCE 7.3 MM

	Teeth distance, 6 σ, mm	
Material	**Sintering 1120°C**	**Sintering1250°C**
Astaloy A + 2%Cu + 0.8%C	0.019	0.034
Astaloy CrM + 0.55%C	0.016	0.016

HIGH PERFORMANCE PM STEELS

In order to achieve mechanical properties similar to wrought steel both alloying combinations with high hardenability and high density must be utilized. The strength is determined on the sintering process in combination with the cooling rate but can be further improved by a separate heat treatment. The density is of greatest importance and preferably this is reached directly during compaction in order to avoid large shrinkage during sintering but can also be increased in subsequent processing steps with for example surface densification or shot peening [5, 6, 9].

Four examples of high performance PM-steels will be described in this paper. These are presented in Table 2.

TABLE 2
HIGH PERFORMANCE PM-STEELS

Powder grade	Alloying method	Alloying composition			
		Cu	Ni	Mo	Cr
Distaloy AE	Diffusion bonding	1.5	4	0.5	-
Distaloy HP	Diffusion bonding + prealloying	2.0	4	1,5	-
Astaloy CrL	Prealloying	-	-	0.2	1.5
Astaloy CrM	Prealloying	-	-	0.5	3.0

Typical properties of these powders when mixed with graphite and lubricant are shown in Table 3. The data in this table shows that highest compressibility is achieved with diffusion alloying and that the prealloyed powders reach similar density after warm compaction. Green strength is almost the same for all materials. GS and GD are measured according to ISO standards.

TABLE 3
PHYSICAL PROPERTIES OF POWDER MIXES INCLUDING 0.5% GRAPHITE

Powder Grade	GS (600MPa)	GD (600MPa)		GD (800 MPa)	
	0.6% Kenolube MPa	0.6% Kenolube	Warm *) compaction	0.6% Kenolube	Warm *) Compaction
Distaloy AE	20	7.15	7.25	7.35	7.40
Distaloy HP	18	7.10	7.25	7.31	7.39
Astaloy CrL	21	7.04	7.18	7.24	7.38
Astaloy CrM	18	6.96	7.10	7.20	7.26

*)Densmix

After pressing and sintering a material based on prealloyed powder achieves higher yield strength and the tensile strength is primarily related to the hardening effect of the alloying elements. Typical mechanical performance after sintering is shown in Table 4.

TABLE 4
TYPICAL PROPERTIES AFTER PRESSING AT 600 MPA AND SINTERING AT 1120°C RESP. 1250°C FOR 30 MIN. 90 N_2/10H_2 COOLING RATE 0.5 – 1.0°C/S.

Material	Ultimate tens. strength MPa		Yield strength MPa		Hardness HV_{10}		Elongation %		Dim. change green-sintered %	
	1120	1250	1120	1250	1120	1250	1120	1250	1120	1250
Distaloy AE+0.5% C*)	750	1000	420	720	220	300	2.5	1.5	-0.14	-0.80
Distaloy HP+0.5% C*)	830	1100	500	800	280	350	1.5	1.5	-0.15	-0.85
Astaloy CrL+0.5% C*)	650	950	520	750	200	220	1.5	2.5	-0.11	-0.65
Astaloy CrM+0.4%C*)	800	1100	600	850	240	310	1.0	2.0	-0.22	-0.75

*) Combined carbon

It is clear that high temperature sintering is beneficial from strength point of view for all four materials. The shrinkage however increases from a level of around 0.2 at 1120°C to 0.8% at 1250°C which in turn influences the dimensional tolerances. All materials achieve a high hardness after high temperature sintering and sizing is therefore difficult. This makes it important to achieve very good tolerances after sintering to avoid or reduce machining.

The difference between ultimate tensile strength and yield strength of the four materials is shown in Figure 7 and 8. After sintering at 1120°C UTS-levels between 520 and 800 MPa are reached and after 1250°C between 800 and 1100 MPa. The yield strength for the prealloyed chromium alloyed steels is higher than that of the diffusion alloyed steels due to the higher hardenability.

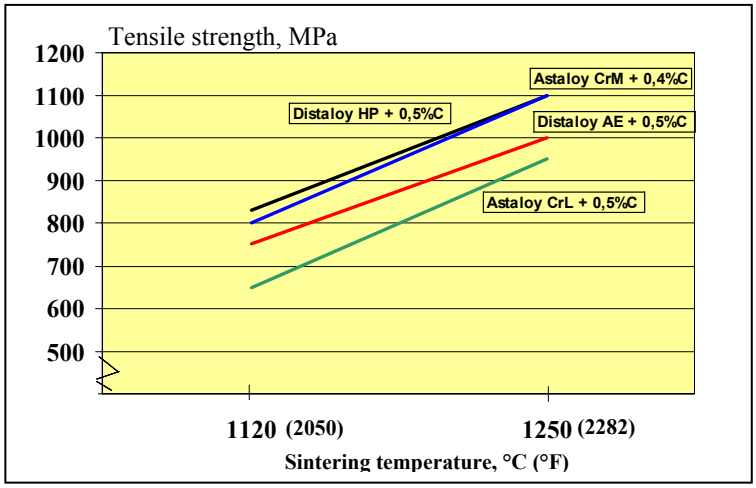


Figure 7: Ultimate tensile strength of four high strength PM steels
(600 MPa; 90 N_2/10H_2; 0.5-1.0°C/s)

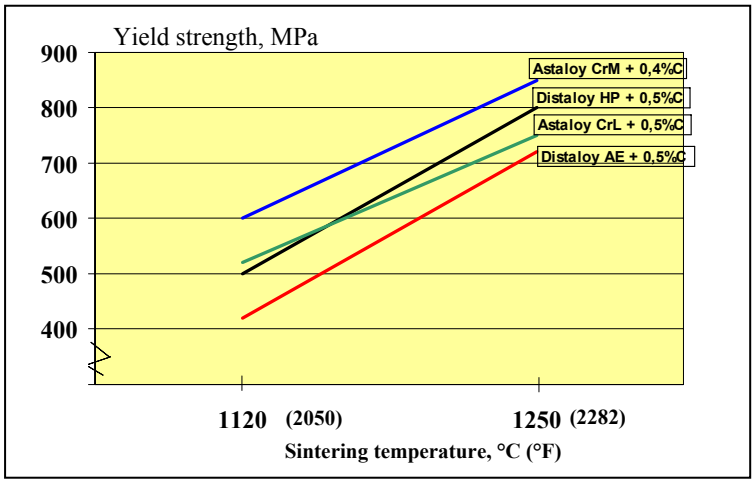


Figure 8: Yield strength of four high strength PM steels
(600 MPa; 90 N_2/10H_2; 0.5-1.0°C/s)

FATIGUE PROPERTIES

The fatigue properties of the above described four materials are strongly dependent on the processing such as compaction, sintering and after treatment but also to a large extent on the geometry of the component. It must also be noted that each component is stressed according to special variable amplitudes depending on the function of the component in the assembly it is used. Therefore fatigue strength data measured on test specimen can only be used as guidelines for the performance of the component in function [7, 10, 11]. However, in order to get a brief understanding of the fatigue performance of these four materials some examples are presented in Figure 9.

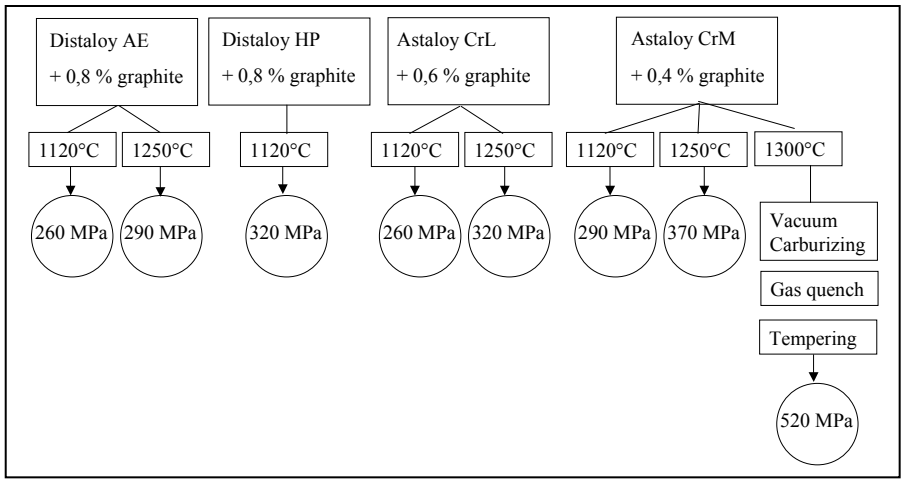


Figure 9: Bending fatigue strength (staircase method, R = -1; 2 million cycles)
Density 7.1 g/cm^3; 1120^{o}C; 30 min. 90N_2; 0.8^{o}C/s

The data in Figure 9 shows that bending fatigue strength in the range 260 – 520 MPa can be achieved with these materials. Both diffusion alloyed materials (Distaloy AE and HP) have a heterogeneous structure which is beneficial for the fatigue performance. This variation in structure on the micro scale prevents cracks for further growth thereby making the material less sensitive to sharp pores or geometrical notches. The materials based on powder prealloyed with chromium have a very high hardenability and high fatigue strength is achieved through the formation of bainite and martensite[8]. Another difference between the materials based on diffusion alloyed and prealloyed powders is that a smaller amount carbon is needed in the chromium containing materials to reach the optimum fatigue performance.

A very high fatigue strength, 520 MPa, is achieved by heat treatment of the material alloyed with 3% Cr and 0.5% Mo. The vacuum carburizing method is advantageous for this type of material due to prevention of any oxidation during the process.

The diffusion-alloyed steel achieves the highest fatigue strength with a combined carbon content of around 0.8%. The diagram in Figure 10 shows the influence of combined carbon content on the fatigue strength after compaction at 600 MPa and sintering at 1120^{o}C. After sintering at this temperature the highest fatigue strength is achieved with Distaloy HP with a carbon content of 0.85%.

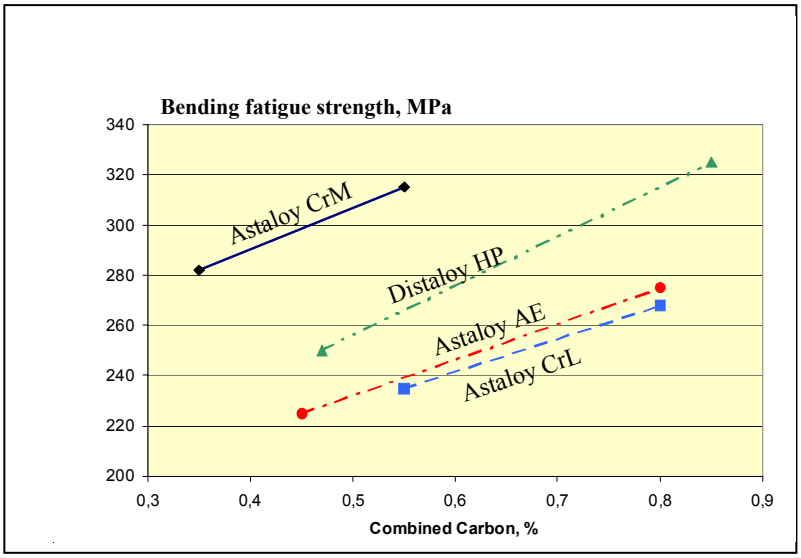


Figure 10: Processing steps and bending fatigue strength (staircase method, R = -1; 2 million cycles) for some high performance PM steels. Pressing 600 MPa and 0.6% Kenolube

DISCUSSION

The two main criteria for the competitiveness of powder metallurgy are strength and dimensional tolerances. By defining the "Playing Field of Powder Metallurgy" as a square with strength resp. tolerances on each axis components and their demand for strength can be characterised in sections of this square. High strength and very good tolerances are the combination with the highest growth potential but still only a minority of the total amount of PM components produced today belongs to this group. Low and medium strength in combination with good tolerances are today representing the bulk of PM parts. This area can be defined as "Defense" resp. "Still Going Strong". The components in the defense area are competing with low strength materials such as plastics and steel sheet forming and continuous cost reductions are necessary to defend these components for powder metallurgy. The components in the "Still Going Strong" area have either a high strength not possible to achieve with plastic or steel sheet or very good dimensional tolerances directly after processing which make other manufacturing technologies less competitive due to high machining costs.

The "Difficult" section at the Powder Metallurgy Playing Field" combines medium to high strength and medium tolerances. Due to less good tolerances machining must be utilized and this in combination with high strength (and high hardness) normally causes costly manufacturing steps. Therefore this section is not a major part of powder metallurgy. However, materials with unique properties not possible to produce with other manufacturing methods have a potential.

The "High Growth Potential" section of the square represents very good dimensional tolerances with medium to high strength. This paper has given examples of low alloyed steels in this section. Depending on processing conditions powders of different types are suitable. Diffusion alloyed powders and prealloyed powders have their respective advantages and alloying elements such as Cr, Ni, Mo and Cu can be adjusted to the demand on the component.

The challenge for suppliers to the automotive industry and other industry segments producing large numbers of identical products is to fulfil not only demands for performance, quality and price but also to be in the frontline for new developments. The powder metallurgy industry is rather young as compared to other manufacturing technologies such as casting, forging and machining of base stock. This gives the opportunity for powder metallurgy to find new improvements not yet known and utilize this for strengthening the competitiveness.

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