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A Survivability Model for Ejection of Green Compacts in Powder Metallurgy Technology

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Abstract

Reliability and quality assurance have become major considerations in the design and manufacture of today's parts and products. Survivability of green compact made by the powder metallurgy technology is considered as one of the major quality attributes in the manufacturing systems today. During powder metallurgy production, the compaction conditions and behavior of the metal powder dictate the stress and density distribution in the green compact prior to sintering. These parameters have great influence on the mechanical properties and overall strength of the final component. In order to improve these properties, higher compaction pressures are usually employed, which make unloading and ejection of green compacts more critical especially for the powder compacted parts with relatively complicated shapes.

This study reports a mathematical survivability model concerning the green compact characteristics in powder metallurgy (PM) technology and the stress-strength failure model in reliability engineering. The model depicts the relationship between mechanical loads (stress) during ejection, experimentally determined green strength, and survivability of green compact. The resulting survivability is the probability that a green compact survives during and after ejection. This survivability model can be used as an efficient tool for selecting the appropriate parameters in process planning stage in powder metallurgy technology. A case study is used to demonstrate the application of the proposed survivability model.

Introduction

Nowadays, the economic environment is becoming increasingly harsh. The emerging world economy is growing the demand to improve the performance of products and manufacturing processes while at the same time reducing their costs. The requirements for minimizing the probability of failures, whether those failures simply increase costs or harm the users in any way, is placing increased emphasize on the reliability.

The powder metallurgy is one the manufacturing processes that is being used particularly for the manufacturing of relatively complex parts. The availability of a wide range of powder compositions, the capability to produce parts to accurate dimensions and the economics of the overall operation have made this process attractive for many applications in different industries like aerospace, biomedical engineering, automotive, machinery and etc. Powder metallurgy has the ability to make near net shape parts at a high material utilization ratio and the flexibility in tailoring material properties to suit the application.

The manufacturing process of a powder compacted part may roughly be divided into two steps. The first step is the compaction of the metal powder (cold die compaction) where plastic deformation of powder particles is the major deformation process, and thus the focus of the present study will be on this step. The second step is the heat treatment or sintering of a compacted part in order to bond the powder particles together.

Die compaction is widely used to characterize the mechanical behavior of powders. During compaction process, the powder undergoes a transformation from a loose state to a dense compacted state. The purposes of compaction process are to obtain the required shape, density, and interparticle metallic contact to make the part sufficiently strong. During PM production, the compaction conditions and the behavior of the metal powder dictate the stress and density distribution in a green compact prior to sintering. These parameters have a great influence on the overall strength of the final part. Therefore, the accurate control of the forces applied during compaction process is critical for ensuring that the required density, strength and dimensional specifications are attained [1].

The formation of a powder compact can roughly be divided into identifiable stages as Filling, Compaction, Unloading and Ejection. One of the most important properties of the powder is the compressibility of a metal powder, which determines the density of the part at a given compaction pressure [2]. Increase in density, which has positive effects on toughness and reliability, increases the volume of material that undergoes plastic deformation before fracture [3]. Powder metallurgy manufacturers usually rely on part density as a mean of controlling part performance. Therefore, they use higher compaction pressures to obtain higher densities and better properties. On the other hand, compaction induces a complex state of stress in the powder [4] and ejection stresses usually increases with compacting pressure [5]. During the ejection cycle, radial stress relaxation occurs as the green compact exits from the die. This can generate a stress state that significantly affects the green compact's characteristics such as surface finish, formation of cracks, and lamination. As a result, unloading and ejection stages can impact a green compact's integrity. For iron powders compacted to very high pressures (typically 800 MPa), press and die deflections become important issues. Under these circumstances for multilevel components, die elastic recovery can be differential during the unloading stage [6]. This imposes loads on the green powder compact that cannot be sustained and leads to the tensile failure or crack formation. Die pressing of the metal powder often results in a powder compact with a non-uniform density distribution, mainly because of friction between the die wall and the powder [7] [8]. Friction is an important factor for all stages that can cause density variation throughout the compacted part.

Minimizing the probability of failures, which may increase costs or hazard risks, requires more emphasis on the reliability analysis. Therefore, a mathematical survivability model is proposed in this study by considering the important factors involved in the cold compaction process as well as the basic principles of reliability modeling. A relationship between strength, stress, and survivability of green compact is investigated to determine the probability that a green compact survives during and after ejection. This survivability model can be used as a tool for selecting the appropriate parameters in process planning stage in PM technology.

Notations

g	Random variable representing green density
$\hat{g}$	Maximum value for g
l	Random variable representing applied load (stress)
n	Number of samples tested
p	Random variable representing compaction pressure
$\hat{p}$	Maximum value for p
r	Random variable representing tensile failure stress
$\hat{r}$	Maximum value for r
S_r	Survivability of green compact
σ_p	Standard deviation of the variable p
σ_r	Standard deviation of the variable r
σ_g	Standard deviation of the variable g
μ_p	Mean value of the variable p
μ_r	Mean value of the variable r
μ_g	Mean value of the variable g
ρ_{pg}	Correlation coefficient between variables p and g
v_{pv}	Covariance between variables p and g

Survivability Model

A primary goal of survivability analysis is to act as an aid in process or product design stage. In powder compaction, and specifically for unloading and ejection stages, it is necessary to estimate the green compact's survivability defined as the probability that the strength of powder compacted part (green strength) is greater than the stresses (loads) applied to the part during unloading and ejection stages. Green compact's strength is a term used in powder metallurgy to characterize the mechanical strength of PM part in the compaction stage. It is the result of bonding force in particle-to-particle metallic contact during the compaction process and subsequent cold welding of the particles [9].

In order to understand the survivability of a green compact, it is necessary to know its failure behavior(s) and also the factors that cause these failures [10]. The survivability model can be constructed for all failure modes when they are well understood. Such a model would then allow lifetime predictions that would also make it possible to take into account the influence of environmental parameters on any particular failure mode. The model in turn can be used as a design tool to improve the survivability of products. As shown in Figure 1, failure is caused by stresses (i.e. tensile stress) applied during unloading and ejection stages. The green compact of a PM part has an inherent strength to withstand such stresses, which may be reduced by specific internal or external conditions. A failure occurs when the stresses exceed the green compact's strength. Undesirable conditions that may happen naturally or artificially, internally or externally, will increase stresses applied to the green compact, and/or reduce the strength of the green compact to tolerate them. The structure presented in Figure 1 is consistent with several simple failure models discussed in literature [11].

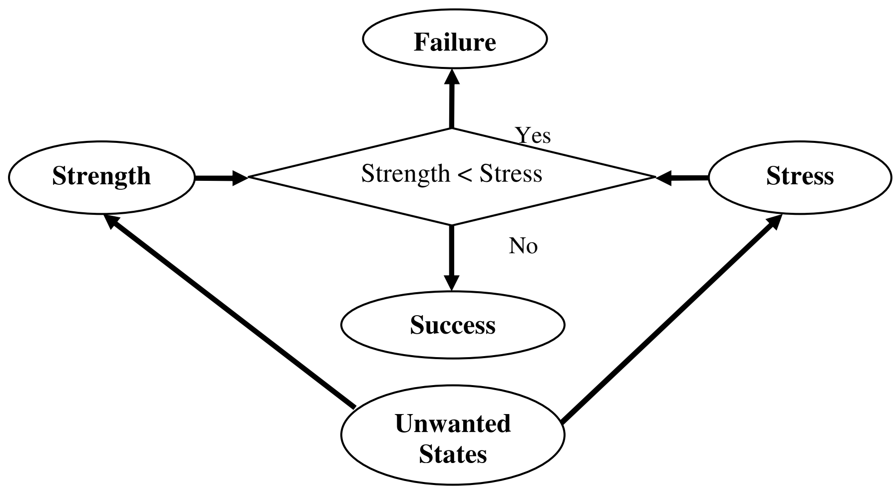

Figure 1: Framework of failure modeling

One of the common failure models for mechanical component is the stress- strength model (also known as load-capacity model) [12]. Based on this failure model, a part fails if and only if the applied load exceeds the part's strength. The load represents an aggregate of the challenge and external conditions (i.e tensile stress during unloading and ejection stages). This failure model may depend on environmental conditions or the occurrence of critical events, rather than the simple passage of time or cycles. Strength is often treated as a random variable representing effects of all conditions influencing the part's strength, or lack of precise knowledge about the part's strength. In this failure model, challenges are caused by failure-inducing agents. Mechanical loads (stresses) are one of the most important failure inducing agents. A comprehensive consideration of survivability requires analysis of this failure-inducing agent.

Mechanical loads (stresses) may be analyzed deterministically (e.g. by identifying the sources of stress), or probabilistically (e.g. by treating stresses as a random variables). In either case, it is necessary to understand why and how such loads (stresses) lead to failure. This would require studying the mechanics of the failure in general and the failure mechanisms in particular. In order to mathematically model the survivability of green compact, a detail understanding of the related failure model is necessary.

Considering the stress-strength failure model, a green compact fails if the applied stresses exceed the green compact's strength. For the powder compacted parts under consideration, the first step is to determine factors, which affect the stress and strength calculations. Also the probability distributions of such influencing factors are required. This information can be obtained from experimental data for a given set of process parameters. Considering the selected failure model, these distributions are then used to compute the survivability of the green compact.

In this study, the compaction pressure and density are considered as major variables affecting the strength of green compact (green strength), and all other parameters are assumed to be constant. Also the tensile stress is assumed to be the only loading factor applied to the green compact during unloading and ejection stages. Therefore, if the probability density function (PDF) for the compaction pressure P is denoted as $f(p)$, then the corresponding cumulative density function (CDF) for the compaction pressure could be defined as:

$$F(p) = \int_0^{\hat{p}} f(p) d_p \tag{1}$$

Similarly, if the PDF for the green compact's density (green density) G is denoted as $f(g)$, then the corresponding CDF for the green density could also be defined as:

$$\mathrm{F}(g) = \int_0^{\hat{g}} f(g) d_g \tag{2}$$

Also, if the PDF for the load (stress) L is denoted as $f(l)$, then the corresponding CDF for the load (stress) could be defined as:

$$F(l) = \int_0^{l} f(l) d_l \tag{3}$$

Considering Eq. (1) and Eq. (2) for the factors affecting the strength of the green compact, the corresponding CDF for the strength of the item under consideration could be defined as:

$$F(s) = \int_0^{\hat{g}} \int_0^{\hat{p}} f(p, g) d_p d_g \tag{4}$$

Where $f(p, g)$ in Eq. (4) is a joint PDF constructed from random variables of compaction pressure and green compact's density, which jointly define a variable "S" representing strength of the green compact. By considering the stress-strength failure model concept and applying Eq. (3) and Eq. (4), the survivability of green compact could be defined as:

$$Sr = \int_0^{\hat{g}} \int_0^{\hat{p}} f(p,g) \left[\int_0^{S} f(l) d_l \right] d_p d_g \quad (5)$$

As defined in Eq. (5), survivability of the green compact is the probability that the powder compacted part will survive the application of loads (stresses) under certain conditions. In the case of high pressure compaction, these critical loads (stresses) are present during unloading and ejection cycle. Die elastic recovery during unloading stage will impose loads (stresses) on the green compact leading to the tensile failure if it cannot be sustained. During the ejection cycle, the striping and sliding pressures are required to get the compact moving inside the die. These pressures that are required to overcome the static and dynamic friction between the powder and the die walls will impose stresses on the green compact during the ejection cycle. These stresses could result in the formation of cracks, and potentially lead to the tensile failure in the ejected powder compacted part.

Since experimental measurement of the imposed stresses during unloading and ejection cycle is difficult, three point bending test results are used in this study to model the green compact's behavior during ejection. Three point bending is a common test for assessing the tensile strength of powder compacted parts. The relation between applied load and tensile failure stress is given by [13]:

$$\sigma = \frac{3Fd}{2bh^2} \quad (6)$$

Where:

σ = Tensile Failure Stress
F = Applied Force (Load)
d = Distance between two supports
b = Width of the specimen
h = Height of the specimen

Therefore, if the PDF for the generated tensile failure stress σ is denoted as $f(r)$, then the corresponding CDF for the tensile failure stress is expressed by:

$$F(r) = \int_0^{\hat{r}} f(r) d_r \quad (7)$$

Based on ISO7438 [14], parameters d, b and h in Eq. (6) should be kept unchanged during three point bending tests, therefore, by replacing the applied load (stress) L with the tensile failure stress σ in Eq. (5), survivability of the green compact could be interpreted as the probability that the green compact's strength exceeds the tensile failure stress, resulting from application of a single load. Therefore:

$$Sr = \int_0^{\hat{g}} \int_0^{\hat{p}} f(p,g) \left[\int_0^{\hat{r}} f(r) d_r \right] d_p d_g \quad (8)$$

Considering the bivariate normal distribution for $f(p,g)$, the correlation between parameters involved in formation of the green compact's strength is assumed to be linear. Also, all the parameters in the proposed survivability model (p , g and r) are assumed to be normally distributed. Therefore $f(r)$ and $f(p,g)$ are defined as follows:

$$f(r) = \frac{1}{\sigma_r\sqrt{2\pi}} e^{-\frac{(r-\mu_r)^2}{2\sigma_r^2}} \tag{9}$$

And

$$f(p,g) = \frac{1}{2\pi\sigma_p\sigma_g\sqrt{1-\rho_{pg}{}^2}} e^{-\frac{z_{pg}}{2(1-\rho_{pg}{}^2)}} \tag{10}$$

Where:

$$z_{pg} = \frac{(p-\mu_p)^2}{\sigma_p^2} - \frac{2\rho_{pg}(p-\mu_p)(g-\mu_g)}{\sigma_p\sigma_g} + \frac{(g-\mu_g)^2}{\sigma_g^2} \tag{11}$$

$$\rho_{pg} = \frac{v_{pg}}{\sigma_p\sigma_g} \tag{12}$$

$$v_{pg} = \frac{1}{n-1}\sum_{i=1}^{n}(p_i-\mu_p)(g_i-\mu_g) \tag{13}$$

Considering the Eq. (8), Eq. (9) and Eq. (10), survivability of the green compact can be expressed by:

$$S_r = \int_0^{\hat{g}}\int_0^{\hat{p}} \frac{1}{2\pi\sigma_p\sigma_g\sqrt{1-\rho_{pg}{}^2}} e^{-\frac{z_{pg}}{2(1-\rho_{pg}{}^2)}} \left[\int_0^{\hat{r}} \frac{1}{\sigma_r\sqrt{2\pi}} e^{-\frac{(r-\mu_r)^2}{2\sigma_r^2}} d_r\right] d_p d_g \tag{14}$$

By obtaining the required data for parameters involved in the proposed survivability model (p , g and r), which are relatively easy to obtain experimentally, the value of survivability for any green compact under consideration can be calculated.

Illustrative Case Study

In order to illustrate the application of the proposed survivability model, experimental data for the green compacts made by die pressing of ferrous powders was used. Five nominal set-points of 100, 150, 200, 265 and 300 MPa were considered for the compaction pressures. Five samples of green compacts were made at each compaction set point. The relative density for each compacted sample was calculated and then, three point bending test was performed accordingly. The geometry of samples was kept the same throughout the experiment.

Using the experimental data and applying Eq. (14), survivability of the green compact at each of the compaction pressures was determined. The result of this calculation is demonstrated in Figure 2.

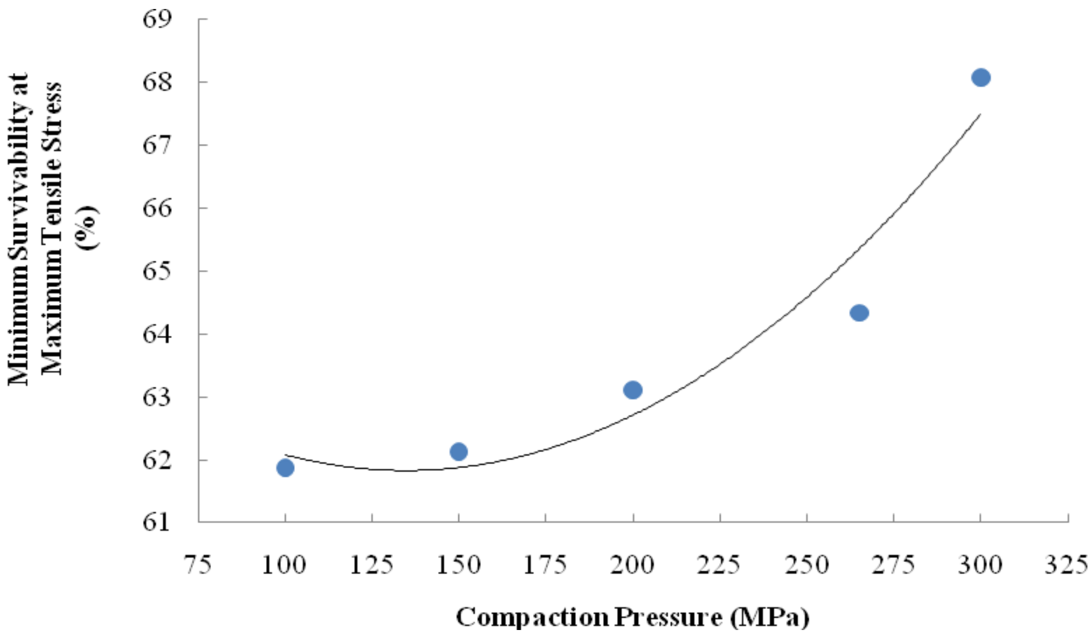

Figure 2: Relation between compaction pressure and minimum survivability at maximum tensile stress during ejection

These results represent the minimum survivability of green compact when the ejection stress (load) is at its maximum level. The ejection stresses applied to the green compact are typically much lower [15], resulting in substantially higher survivability. To explore the situations when the stress applied to the powder compacted part during ejection is less than maximum tensile strength, the proposed model was used to calculate the survivability of green compact when the ejection stresses are 5, 10, 25, 50, 75, 87.5 and 100% of the average tensile failure stress at each compaction pressure. For every considered level of ejection stress, the same standard deviation (extracted from the experimental data for tensile failure stress) was used to generate 10 sets of data. Applying the proposed model and using this data, the survivability was calculated for each set of data separately. The mean of calculated values was considered as survivability of green compact for that particular ejection stress at each compaction pressure. The results are shown in Table 1.

Analysis of the results collected in Table 1 verifies that for ferrous powder used, under the compaction pressure of 150MPa for example, an increase in the ejection stress from 1.12 to 22.45MPa, results in reduction of survivability from 74.05 to 68.71%. Similarly at the compaction pressure of 300MPa (the highest compaction pressure used in this study), if the ejection stress increases from 2.20 to 43.86MPa, the survivability of green compact will reduce from 78.06 to 71.86%.

Table 1: Ejection stresses and survivability of green compact at each compaction pressure

Compaction Pressure (MPa)	**Ejection Stress (MPa)**	**Survivability (%)**
100	0.76	74.14
	1.52	74.01
	3.80	73.73
	7.60	73.04
	11.38	72.33
	13.27	71.52
	15.17	70.71
150	1.12	74.05
	2.25	73.04
	5.61	72.25
	11.22	71.31
	16.84	70.40
	19.64	69.65
	22.45	68.71
200	1.50	73.14
	3.00	72.81
	7.52	71.33
	15.05	70.66
	22.56	69.84
	26.32	68.37
	30.07	67.77
265	1.87	74.10
	3.73	74.02
	9.33	73.34
	18.65	72.49
	27.98	71.92
	32.64	70.58
	37.31	69.35
300	2.20	78.06
	4.39	77.36
	10.98	75.32
	21.93	74.32
	32.90	73.70
	38.39	72.86
	43.86	71.86

To create a more comprehensive model for the survivability of green compact during ejection stage, the experimental data was used to fit a continuous curve representing the relation between survivability and ejection stress. Since survivability against ejection will be 100% when the tensile stresses are absent, the following function form was found to be the most suitable:

$$\hat{S}_r = (100 - S_{min})e^{-k\sigma_{max}} + S_{min} \tag{15}$$

Where:

$\hat{S}_r$ = Survivability curve

S_{min} = Minimum survivability at maximum ejection stress

σ_{max} = Maximum ejection stress

k = Model parameter

Using the data in Table 1, the required parameters for survivability curve was calculated as shown in Table 2.

Table 2: Parameters of the survivability function form

Compaction Pressure (MPa)	σ_{max} **(MPa)**	***K***	S_{min} **(%)**
100	≤ 15.17	3.5512	72.5060
150	≤ 22.45	1.2720	70.7409
200	≤ 30.07	1.3813	69.9567
265	≤ 37.31	1.8285	71.8518
300	≤ 43.86	0.7415	73.9243

By applying the Eq. (15) the survivability of green compact against different ejection stresses at compaction pressures of 150 and 300 MPa are shown in Figures 3 and 4.

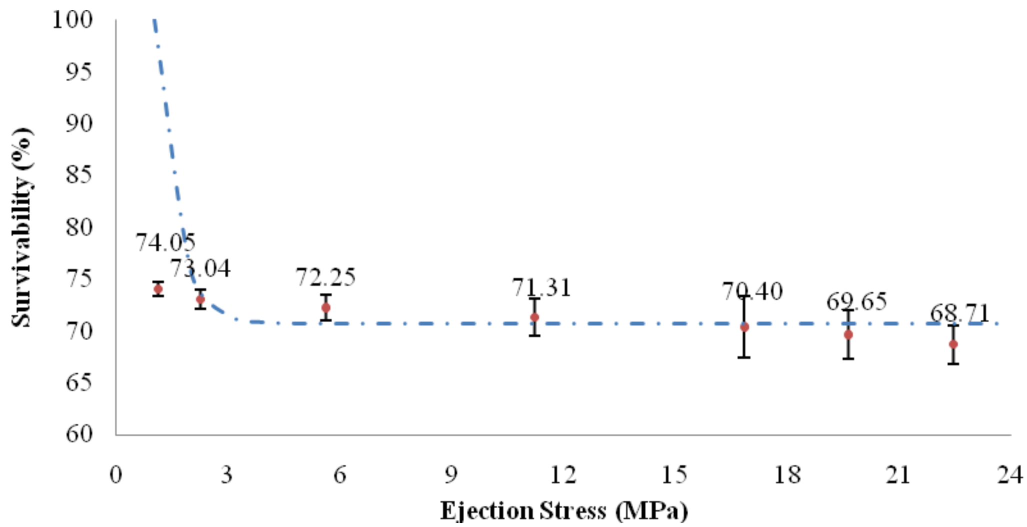

Figure3: Survivability behavior against ejection stress at 150MPa compaction pressure(α =5%)

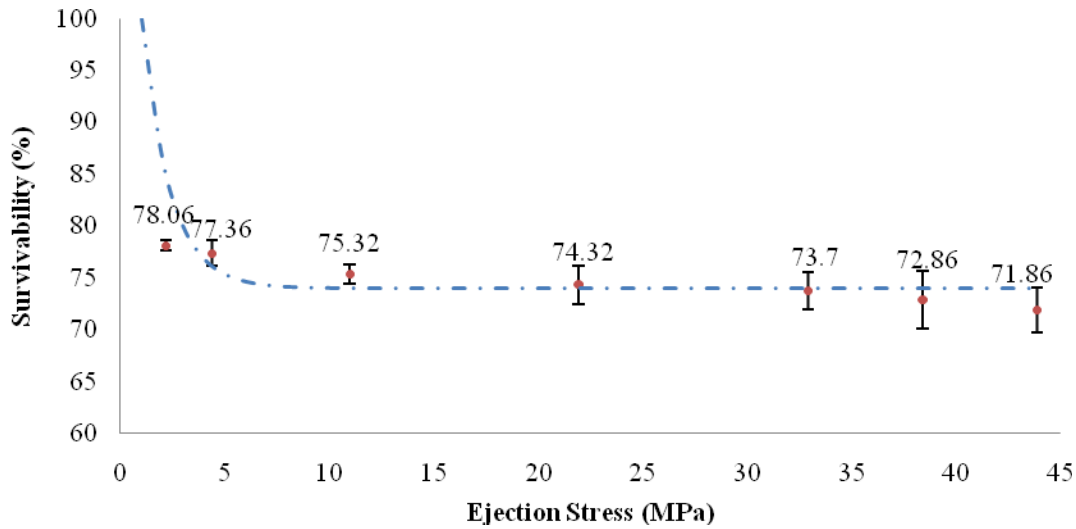

Figure4: Survivability behavior against ejection stress at 300MPa compaction pressure(α =5%)

By using the information in Figure 2, one can easily evaluate the survivability of a green compact with a compaction pressure in the range of 100 to 300 MPa. If the ejection stresses present during ejection stage are known, by using the information in Table 2 and applying the Eq. (15) the survivability of the green compact can be evaluated. This makes it possible to evaluate the effect of various process parameters on the process yield, and make the appropriate decisions accordingly.

High yield of green compacts prior to sintering is of prime importance and being able to calculate the survivability against ejection stresses will be beneficial. Therefore, by controlling the compaction process, manufacturers can ensure that the desirable density, required strength and the desired yield will be attained. The proposed survivability model can be used as an effective tool for proper selection of design parameters.

Conclusion

It is necessary to take into account the manufacturing capabilities and limitations as well as the material data in order to reduce design iteration and to minimize the trial and error required at the manufacturing stage. Die compaction process results in a powder compacted part with an inhomogeneous density distribution. The higher the green density (density after compaction), the higher will be the strength of the powder compacted part and hence, the greater will be the green compact's resistance to external forces. Considering the green compact's integrity, both unloading and ejection stages can be crucial. The tool deflection during compaction and elastic recovery in unloading stage, along with the ejection stresses are important considerations since they impose loads on the green compact which may not be sustainable and ultimately lead to the tensile failure.

In this study, a mathematical survivability model based on the stress-strength failure model was developed. In order to illustrate the application of the proposed survivability model, results from three point bending tests, representing the state of maximum possible stress during and after ejection stage were employed. It was shown that the survivability of green compact was improved by increasing the compaction pressures from 100 to 300 MPa (the selected range for the compaction pressures). It was also shown that for each compaction pressure, decrease in tensile failure stress will increase survivability of the green compact during ejection. Considering the fact that ejection stresses applied to the green compact are typically lower than its maximum tensile strength, the proposed survivability model was also used to calculate the survivability of green compact when the ejection stresses vary between 5 to 100% of the average tensile failure stress at each compaction pressure. The statistical analysis of these calculations confirmed that increasing values of stress during ejection cycle would cause the survivability of green compact to decrease exponentially. For the powder compacted parts with more complicated geometry, finite element model is being employed to estimate the stresses applied to the green compact during ejection cycle. The results will be used to demonstrate the application of the proposed survivability model.

It is necessary to consider that design and manufacturing must be closely interrelated and they should never be viewed as separate disciplines or activities. Careful design, using the best established design practices, computational tools, and manufacturing techniques, are the optimum approach for achieving high quality products and realizing cost savings.

References

[1] Smith, L.N.; Midha, R.P.; Graham, A.D. Simulation of metal powder compaction, for the development of a knowledge based powder metallurgy process advisor. *Journal of Materials Processing Technology* 1998, 79 (1-3), 94-100.

[2] Senthilvelan, T.; Raghukandan, K.; Venkatraman, A. Testing and Quality Standards for Powder Metallurgy Products. *Materials and Manufacturing Processes* 2003, 18 (1), 105-112.

[3] Straffelini, G.; Molinari, A. Microstructure and mechanical reliability of powder metallurgy (P/M) Ferrous Alloys. *Journal of Materials Engineering and Performance* 1996, 5 (1), 27-33.

[4] Briscoe, B.J.; Rough, S.L. The effects of wall friction in powder compaction. C*olloids and Surfaces, A: Physicochemical and Engineering Aspects* 1998, 137(1-3), 103-116.

[5] Lefebvre, L.P.; Mongeon, P.E. Effect of tool coatings on ejection characteristics of iron powder compacts. *Powder Metallurgy* 2003, 46 (1), 43-48.

[6] Korachkin, D.; Gethin, D.T.; Lewis, R.W.; Tweed, J.H.; Guyoncourt, D. M.M. Measurement of Young's modulus and tensile failure properties of green powder compacts. *Powder Metallurgy*, 2008, 51 (2), 150-159.

[7] Redanz, P. Numerical modeling of cold compaction of metal powder. *International Journal of Mechanical Science* 1998, 40 (11), 1175-1189.

[8] Sopchak, N. D.; Misiolek, W. Z. Density Gradients in Multilayer Compacted Iron Powder Parts. *Materials and Manufacturing Processes* 2000, 15 (1), 65-79.

[9] Senthilvelan, T.; Raghukandan, K.; Venkatraman, A. Tooling Design and Compaction Analysis on P/M Copper Bushes. *Materials and Manufacturing Processes* 2003, 18 (1), 113-122.

[10] DeWolf, I. MEMS reliability. *Microelectronics Reliability*, 2003, 43 (7), 1047-1048.

[11] Dasgupta, A.; Pecht, M. Materials Failure Mechanisms and Damage Models. *IEEE Transactions on Reliability* 1991, 40 (5), 531-536.

[12] Lewis, E.E.; Chen, H.C. Load-Capacity Interference and the Bathtub Curve. *IEEE Transactions on Reliability* 1994, 43 (3), 470-475.

[13] Poquillon, D.; Baco-Carles, V.; Tailhades, Ph.; Andrieu, E. Cold compaction of iron powders – relations between powder morphology and mechanical properties Part II: Bending tests, results and analysis. *Powder Technology*, 2002, 126 (1), 75-84.

[14] ISO7438. Metallic Materials – Bend Test, 1985.

[15] Redanz, P. A study of stresses in powder compacted components during and after ejection. *International Journal of Solids and Structures* 2001, 38 (5), 759-775.

Biography

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