CALCULATION OF LIMIT PRESSURE OF A DIE ASSEMBLY IN COMPACTION OF METAL ALLOY POWDER

https://doi.org/10.22533/at.ed.804112520039

Data de aceite: 03/09/2025

Raphael Basilio Pires Nonato
Universidade de Sorocaba (UNISO) e Instituto Federal de Santa Catarina (IFSC)
Programa de Pós-graduação em Processos Tecnológicos e Ambientais e Departamento de Fabricação Mecânica (F23)
Sorocaba – SP e Chapecó – SC
http://lattes.cnpq.br/9331089672178927

Norberto Aranha
Universidade de Sorocaba (UNISO)
Programa de Pós-graduação em Processos Tecnológicos e Ambientais
Sorocaba – SP
http://lattes.cnpq.br/1908333432529833

Thomaz Augusto Guisard Restivo
Universidade de Sorocaba (UNISO)
Programa de Pós-graduação em Processos Tecnológicos e Ambientais
Sorocaba – SP
http://lattes.cnpq.br/7327617106070962

José Carlos Machado Junior
Universidade de Sorocaba (UNISO)
Programa de Pós-graduação em Processos Tecnológicos e Ambientais
Sorocaba – SP
http://lattes.cnpq.br/ 2311635580427250

ABSTRACT: Suitable compaction pressure of metal alloy powders is crucial in providing raw material with the required characteristics for post-processing. The densification phenomenon is controlled by the intensity of the compaction, which affects the mechanical resistance of the compacted. Thus, the limit load of a die was determined based on the interpolation of results of stress obtained via simulations in the finite element method keeping the discretization strategy. The interpolated function can also be used to determine von Mises stress of a known applied pressure. The simulations were conducted via the finite element method inputting the limit load obtained via interpolation function and presented a relative error of 8.5×10^{-4}%. This result addresses that, instead of being determined by trial-and-error approach, the limit load of the die could be obtained via the combination of few simulations and the calculation of an interpolation function.

KEYWORDS: Limit load, Die, Powder compaction, structural analysis, Powder metallurgy.

CÁLCULO DE CARGA LIMITE DE UMA MATRIZ EM COMPACTAÇÃO DE PÓ DE LIGA METÁLICA

RESUMO: A pressão de compactação adequada de pós de ligas metálicas é crucial para fornecer à matéria-prima as características necessárias para o pós-processamento. O fenômeno de densificação é controlado pela intensidade da compactação, que afeta a resistência mecânica do compactado. Assim, a carga limite de uma matriz foi determinada com base na interpolação dos resultados de tensão obtidos por meio de simulações no método dos elementos finitos, mantendo a estratégia de discretização. A função interpolada também pode ser usada para determinar a tensão de von Mises de uma pressão aplicada conhecida. As simulações foram conduzidas pelo método dos elementos finitos, inserindo a carga limite obtida por meio da função de interpolação, e apresentaram um erro relativo de 8.5 x 10^{-4}%. Este resultado demonstra que, em vez de ser determinada por tentativa e erro, a carga limite da matriz pode ser obtida por meio da combinação de algumas simulações e do cálculo de uma função de interpolação.

PALAVRAS-CHAVE: Carga limite, Matriz, Compactação de pó, Análise estrutural, Metalurgia do pó.

INTRODUCTION

Powder metallurgy (PM) aims to obtain a solid shape as product from wet raw powder. In the case of metal alloys, first the alloy is theoretically designed to fulfill the customer requirements. After its design, the weighing of each powder element is made to assure the proportionality between the alloy elements. Subsequently, all the weighted element powders are mixed as homogenously as possible, put into the die chamber, and pressed to assume the shape of the die (Thümmler; Oberacker, 1993).

In view of this, there are many challenges in PM of metal alloys, one of them being the application of an adequate pressure to the metal alloy powder via pressing equipment over a punch in a die assembly. The pressure load plays significant role in the obtainment of mechanical properties, as the compaction degree dictates the porosity of the compacted.

In addition to the application of adequate compaction pressure, the compacted is often subjected to conventional post-processing, which involves heat treatment to improve mechanical properties, metallurgical characteristics, and geometric parameters (Upadhyaya, 2002) (Restivo *et al.*, 2023) (Maurya *et al.*, 2025). Moreover, alternative post-processing encompasses powder conditioning, among others.

Nevertheless, the type of powder compaction, which is within the scope of this paper, refers to cold axial compaction via punching (see Figure 1).

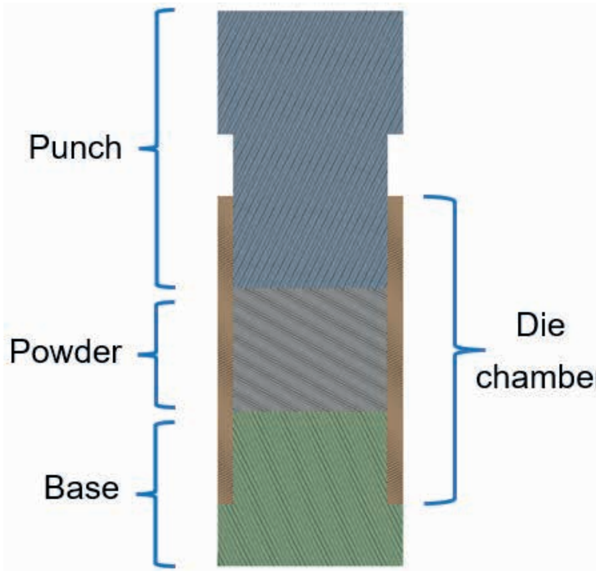

Figure 1: Schematic of cold axial compaction (die assembly).

Source: Own authorship, 2025.

The type of press shown in Figure 1 demands rigidity much greater than that of the compacted powder mass. The die chamber receives the powder mass, which receives the vertical load from the punch above. The vertical top-down movement of the punch (when in contact with the powder) is the responsible for pressing the powder against the base and the die chamber, causing the compaction of the powder (Nonato; Restivo, 2023).

Double axial cold compaction pressure of 275 MPa (with a dwell period of 10 minutes) was applied to aluminum matrix composites. The pellet obtained from the compaction was subsequently sintered and subjected to thermomechanical treatment (hot extrusion) to investigate the effect of hot extrusion on tribological and mechanical behavior of these composites (Mohapatra; Maity, 2017).

The compacting behavior of pure aluminum, Alumix 13, and Alumix 13 reinforced with 15 wt.% Saffil short fibers was studied in what refers to densification. The samples were axially cold compacted with pressures between 250 and 386 MPa from 25 to 126 minutes (Moreno; Oliver, 2011).

Al + 5 Mg + Gr + 4 Zr powder was double axially cold compacted with 275 MPa, sintered, and hot extruded to investigate its tribo-mechanical properties at room temperature (Mohapatra *et al.*, 2019).

Al 6061 nanocrystalline matrix reinforced with multi-walled carbon nanotubes were obtained by mechanical alloying. The powder was subjected to cold uniaxial compaction, and sinterization to study lattice parameters, relative density, compressibility sinterability, hardness, and green compressive strength (Jeyasimman *et al.*, 2014).

Aluminum-boron carbide composites with variable boron carbide proportion were obtained via powder metallurgy to investigate their hardness, cold compaction behavior, and micro-structural behavior (Damtew; Thiyagarajan, 2021).

Therefore, in this paper, a die assembly is subjected to simulations to establish correspondence between the applied pressure and von Mises stress via interpolating function aiming to calculate its limit load.

MATERIAL AND METHODS

The process followed by this paper is based on the stages described in Figure 2. The first step consists of defining the boundary conditions of the die assembly. The second stage refers to defining the discretization strategy. The set of simulations is performed in the third step to generate corresponding values of applied pressure and maximum von Mises stress in Ansys® software. In the fourth stage, the set of points are input for generating an interpolation function (which input is maximum von Mises stress), and the output is the pressure applied to the punch. The calculation of the limit pressure is then made by substituting the maximum stress by the yield strength of the material in the interpolation equation just generated (fifth step). The calculated value for the limit pressure feeds another simulation to check if it corresponds to the referred stress (sixth stage).

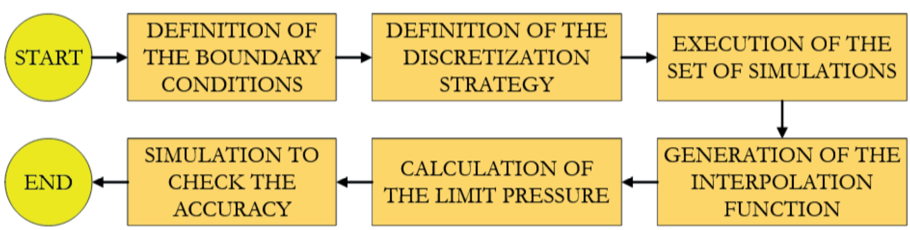

Figure 1: Flowchart of the main process applied in this work.

Source: Own authorship, 2025.

The boundary conditions and the dimensions of the problem are schematically represented in Figure 2.

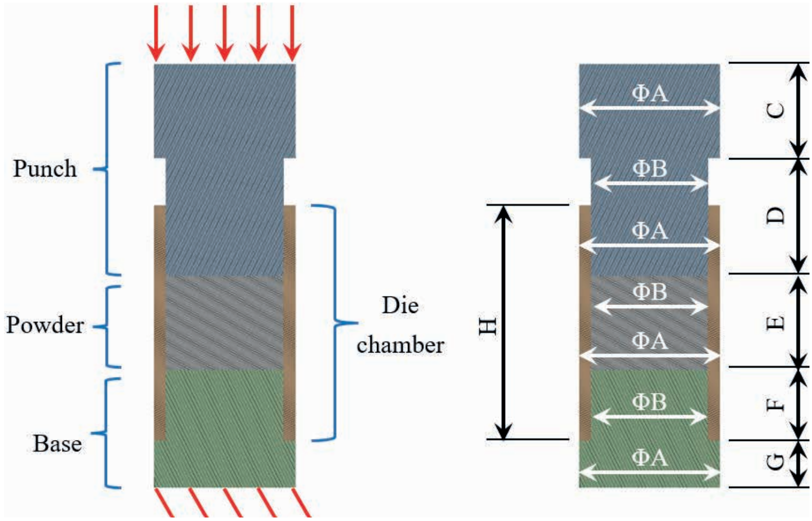

Figure 2: Boundary conditions and dimensions of the die assembly.

Source: Own authorship, 2025.

According to the scheme, the lower surface of the base is clamped, and the pressure load is applied over the upper surface of the punch. The dimensions are symbolically assigned in Figure 2, and their corresponding values can be checked in Table 1.

Part	Dimensions (mm)	Material	Elasticity modulus (GPa)	Poisson's ratio	Density (kg/m^3)	Yield strength (MPa)
Punch	A = 32; B = 24; C = 15; D = 23.	AISI D2	207	0.28	7700	1500
Base	A = 32; B = 24; F = 15; G = 10.	AISI D2	207	0.28	7700	1500
Die chamber	A = 32; B = 24; H = 50.	AISI D3	190	0.27	7860	2000
Metal powder	B = 24; E = 18.	AlCoCrFeNi	91.5	0.3	3577	750

Table 1: Dimensions and material properties of the die assembly.

Source: Own authorship, 2025.

Three distinct runs were performed in Ansys®: (a) one with a pressure that corresponds to a maximum von Mises stress lower than the yield strength of the material with the lowest yield strength (in this case, either punch or base); (b) other with an intermediate pressure value (which corresponds to a value that may be lower or greater than the minimum yield strength; (c) the last one with a pressure that corresponds to a stress higher than the lowest yield strength. Therefore, in the first run, the applied pressure was 600 MPa, the second was 650 MPa, and the third was 700 MPa.

The discretization strategy adopted was the program-controlled refinement method, resulting in elements of the order of 2 mm. The type of element selected was the tetrahedral with 10 nodes, and the number of nodes and elements are, respectively, 11536 and 5661.

RESULTS AND DISCUSSION

The set of simulations was executed, resulting in the values of maximum von Mises stress (1425.5, 1545.7, and 1666 MPa), respectively, for each value of applied pressure (600, 650, and 700 MPa) as per Table 2. The plot of von Mises stresses is shown in Figure 3.

Pressure (MPa)	Von Mises stress (MPa)
600	1425.50
650	1545.70
700	1666.00

Table 2. Applied pressures, and their corresponding maximum von Mises stresses.

Source: Own authorship, 2025.

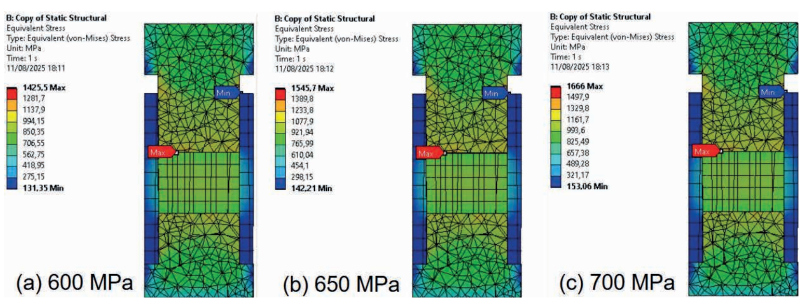

Figure 3: von Mises stress plots of the die assembly for pressures of 600, 650, and 700 MPa.

Source: Own authorship, 2025.

The function generated by interpolation corresponds to Equation 1, in which is the applied pressure (in MPa), and is the maximum von Mises stress (also in MPa). A second-degree polynomial was applied to interpolate pressure and stress due to the nature of the finite element selected for this discretization.

$$f(x) = \frac{1}{50000}x^2 + \frac{2379}{1000}x - \frac{91}{10} \quad (1)$$

Therefore, the calculation of the limit pressure is made by substituting 1500 MPa in the place of in Equation 1, in which 630.99 MPa was the calculated pressure. This implies a relative error of 8.15 x 10^{-4}%, which represents good accuracy in the prediction of values in the range between 600 and 700 MPa. Figure 4 shows von Mises stress plot, where the limit pressure is applied to the upper surface of the punch, resulting in the maximum stress of 1500 MPa at the lower surface of the punch, which is the threshold of the yielding phenomenon.

Figure 4 also indicates that the die chamber is oversized when comparing their yield strength to the involved stresses (between 138.08 and 440.74 MPa). The base and the punch are underutilized (except for the narrow region that encompasses the lower surface of the punch), where the range of stress goes from 138.08 to 1197.4 MPa. On the other hand, metal powder presented stresses varying from 743.39 to 1046.1 MPa, which assures that the entire powder mass will plasticize, improving the posterior sintering of the compacted.

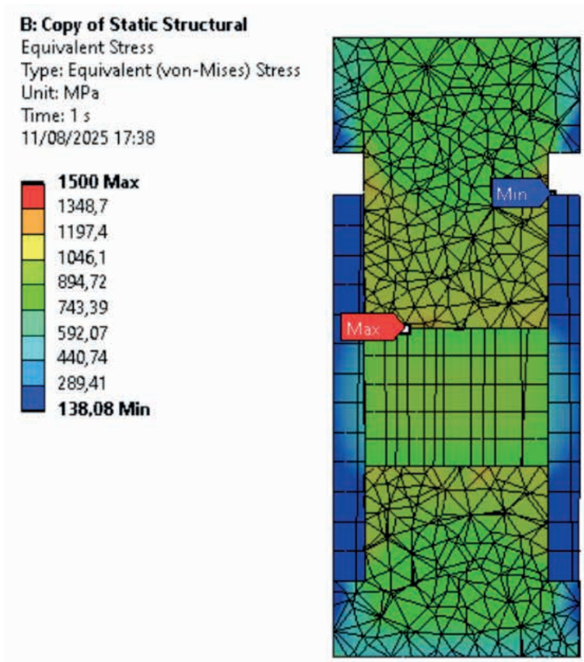

Figure 4: von Mises stress plot of the limit condition of applied pressure (631 MPa).

Source: Own authorship, 2025.

According to Figure 4, improvements in the die assembly can be made in the branch of material reduction, assuming that the dimensions of the metal alloy powder cannot be changed. Thenceforth, for example, the thickness of the die chamber can be reduced, the height of the head of the punch can be shortened, the height of the lower part of the punch can be reduced. The changes in the base can be analogous to those described for the punch.

CONCLUSIONS

The general objective of obtaining a mathematical expression to calculate the limit pressure applied to the punch of a die assembly was accomplished. Therefore, the die assembly studied herein has the limit condition of applied pressure of 631 MPa, which approximately corresponds to 1500 MPa of stress.

The technique of applying three values of pressures (one lower, one intermediate, and another higher than the required to induce the yielding of the material) was successfully implemented due to the nature of the finite element selected in the discretization of the domain of the die assembly.

ACKNOWLEDGEMENTS

The authors would acknowledge the research councils CNPq (proj. 408406/2021-6), CatalisaICT Sebrae (proj. 29083*128) and FAPESP (proj. 2023/09818-8) for financial support.

REFERENCES

DAMTEW, A. W.; THIYAGARAJAN, R. Experimental testing and fabrication of metal matrix composite for automotive applications. International Journal of Materials Science and Applications, 10:6, p. 134-140, 2021. http://dx.doi.org/10.11648/j.ijmsa.20211006.12

JEYASIMMAN, D.; SIVAPRASAD, K.; SIVASANKARAN, S.; NARAYANASAMY, R. Fabrication and consolidation behavior of Al 6061 nanocomposite powders reinforced by multi-walled carbon nanotubes. Powder Technology, 258, p. 189-197, 2014. http://dx.doi.org/10.1016/j.powtec.2014.03.039.

MAURYA, H. S.; MARCZYK, J.; JUHANI, K.; SERGEJEV, F.; KUMAR, R.; HUSSAIN, A.; AKHTAR, F.; HEBDA, M.; PRASHANTH, K. G. Binder jetting 3D printing of green TiC-FeCr based cermets- Effect of sintering temperature and systematic comparison study with laser powder bed fusion fabricated parts. Materials Today Advances, 25:100562, 2025. https://doi.org/10.1016/j.mtadv.2025.100562.

MOHAPATRA, S. K.; MAITY, K. Sintering and characterisation of hot extruded aluminum-based MMC developed by powder metallurgy route. International Journal of Mechanical and Materials Engineering, 12:2, p. 1-9, 2017. https://doi.org/10.1186/s40712-016-0068-9.

MOHAPATRA, S. K.; MISHRA, S. B.; JOSHI, K. K.; PRADHAN, S. Effect of the hot deformation on mechanical and wear characteristics of the P/M AMC. Materials Today: Proceedings, 18, p. 5040-5047, 2019. https://doi.org/10.1016/j.matpr.2019.07.498.

MORENO, M. F.; GONZÁLEZ OLIVER, C. J. R. Densification of Al poder and Al-Cu matrix composite (reinforced with 15% Saffil short fibres) during axial cold compaction. Powder Technology, 206, p. 297-305, 2011. http://dx.doi.org/10.1016/j.powtec.2010.09.034.

NONATO, R. B. P.; RESTIVO, T. A. G. Software for densification calculation in sintering of flat cylinders. In: RAMOS, J. (org.). Open Science Research. Guarujá:Editora Científica Digital, 2023a, 1st ed., p. 1484-1496. Available in: <https://downloads.editoracientifica.com.br/articles/230111718.pdf>. Access in: 28/07/2025.

RESTIVO, T. A. G.; NONATO, R. B. P.; FIGUEIRA, R. R.; FERREIRA, O. A.; PADOVANI, C.; ARANHA, N.; BALDO, D.; SILVA, C. G.; DURAZZO, M. Sintering of metallic diamond alloy powders. Journal of Thermal Analysis and Calorimetry, 148, p. 13003-13009, 2023. https://doi.org/10.1007/s10973-023-12260-8.

THÜMMLER, F.; OBERACKER, R. An introduction to powder metallurgy. London: The institute of materials, 1993.

UPADHYAYA, G. S. Powder Metallurgy Technology. Cambridge International Science Publishing, Cambridge, England, 160 p., 2002.