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CONSTRUCTION OF A MULTI-ELEMENT CONTAINER AND ITS PRACTICAL APPLICATION

CONSTRUÇÃO DE UM RECIPIENTE MULTI-ELEMENTO E A SUA APLICAÇÃO PRÁTICA

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ABSTRACT
The objective of this work is to develop the basic theory of elaboration principles for the optimized construction of multi-element containers. For this purpose, two constructions were studied: the container formed by any number of sleeves and the thin-walled sleeve wrapped with a pre-tensioned steel ribbon. The optimized structure of a multi-element container requires the correlation $K_i^2 \cdot \sigma_i = const$ to be maintained, where: K_i = coefficient of thickness of the thick wall; σ_i = allowable stress on the internal diameter of sleeve “i”. The dependence obtained between the dimensions of the container, the number of elements, and its mechanical properties delimit construction. The study found that winding steel ribbon around the core, steel sleeve, doubles the capacity limits of the container. The developed work allows basic questions arising during the design of the new compound containers to be solved.
Keywords: High pressure; Compound container; Extrusion; Compaction.

RESUMO
O objetivo deste trabalho foi desenvolver a teoria básica dos princípios de construção otimizada de recipientes multielemento. Para esta finalidade, duas construções foram estudadas: o recipiente formado por número qualquer de mangas e o recipiente de parede fina envolvida com uma fita de aço pré-tensionado. A estrutura otimizada de um recipiente multielemento requer que a correlação $K_i^2 \cdot \sigma_i = const$ seja mantida, em que: K_i = coeficiente de espessura de parede, σ_i = tensão admissível sobre o diâmetro interno da manga de "i". A dependência obtido entre as dimensões do recipiente, o número de elementos e as suas propriedades mecânicas delimitam a construção. O estudo constatou que a fita sinuosa de aço ao redor do núcleo, luva de aço, duplica os limites de capacidade do recipiente. O trabalho desenvolvido permite que questões básicas que surgem durante a concepção de novos recipientes compostos possam ser resolvidos.
Palavras-chave: Alta pressão; Recipiente composto; Extrusão; Compactação.

1 – INTRODUCTION

The main component for the efficient operation of devices used for processes such as hot and cold extrusion, the cold hydrostatic compression of powders under pressures of up to 2.0 GPa, and the hot compaction of powders in high isostatic pressure equipment (HIP) devices is a container composed of multi-sleeves (PUGH, 2007a; PUGH, 2007b; KRIVINOS, MAGAZINER and PODGUAETSKY, 1984; RAES, 1983; BOBROVNITCHII, RAMALHO and FILGUEIRA, 2002; BOBROVNITCHII, RAMALHO and SIDERIS, 2003). Industrial experience, the development of equipment, and experimental research have shown that the technological capacity and exploratory quality of extrusion presses are often determined by the working capacity of the containers (KRIVONOS, MAGAZINER and PODGUAETSKY, 1984; BOBROVNITCHII, RAMALHO and SIDERIS, 2003).

The container’s resistance limits the possibility of manufacturing certain parts. In some cases, it is impossible to use the full force of the press because the dimensions of the work area do not allow a container capable of withstanding the required load to be installed (BOBROVNITCHII, RAMALHO and SIDERIS, 2004). For example, due to high specific pressures and high temperatures (440 to 480 °C) and despite the use of the best steels produced by industry, the containers for extrusion presses with increased working power can only be used for a small number (from an economic point of view) of loadings, ranging between 150 and 400 operations (BOBROVNITCHII, RAMALHO and SIDERIS, 2003; DAWSON, 1979).

To solve problems like those mentioned and to attempt to optimize the construction of multi-element-derived containers, theoretical and experimental studies have been conducted on the stress-strain state of the containers, the development of methods for their calculation, and the development of their optimized construction (BOBROVNITCHII *et al.*, 2006; BOBROVNITCHII, RAMALHO and SIDERIS, 2005; BOBROVNITCHII, RAMALHO and SIDERIS, 2004; BOBROVNITCHII and RAMALHO, 2002a; DAWSON, 1979).

In these studies, it was found that there is a simple relationship between the radii of the sleeves and the tightness caused by the difference in diameters during assembly. Thus, the multi-element container with mechanical properties determined by the material of the sleeves and the dimensions selected will generate higher internal pressures (BOBROVNITCHII, RAMALHO and FILGUEIRA, 2002; BOBROVNITCHII, RAMALHO and SIDERIS, 2003; SOMERS, 1988; BOBROVNITCHII *et al*., 2006; BOBROVNITCHII, RAMALHO and SIDERIS, 2005; BOBROVNITCHII, RAMALHO and SIDERIS, 2004; BOBROVNITCHII and RAMALHO, 2002b; DAWSON, 1979). Thus, this study aims to develop a basic theory of the principles of optimized construction of multi-element containers.

2 – OPTIMIZATION THEORY

The general condition for guaranteeing the working capacity of a container is the optimization of its construction (DAWSON, 1979). Optimized construction for a multi-element container is understood as the set of sleeve diameters and their tightness to ensure the following:

a) The lowest possible stresses for the sleeves with fixed internal and external diameters when subjected to internal pressure and

b) The mechanical properties of the sleeves and an internal pressure for the most advantageous correlation of the internal and external diameters (r/R).

To develop the multi-element container, the condition presented in Equation (1) must be maintained (BOBROVNITCHII, RAMALHO and SIDERIS, 2003).

$$K_i^2 \cdot \sigma_i = const \qquad (1)$$

Where: K_i is the coefficient of the thick wall of any free sleeve "i" and is defined by $K_i = r_i / r_{i+1}$ i.e. r is the container's internal radius; σ_i is the allowable stress for the material of sleeve "i" and is defined by $\sigma_i = \sigma_{esc} / n_s$, where: σ_{esc} is the yield strength and we the safety coefficient.

According to a recent study (BOBROVNITCHII, RAMALHO and SIDERIS, 2003), the optimized container dimensions are linked to the maximum allowable pressure p_{max} applied to radius "r", defined by Equation (2).

$$\frac{r}{R} = \sqrt{\left(\frac{\sigma_a}{\sigma_g} - \frac{2 \cdot p_{max}}{n \cdot \sigma_g} \right)^n} \qquad (2)$$

Where:
r is the container's internal radius;
R is the container's external radius;
n is the number of sleeves or rings in the container;
σ_a is the arithmetic mean of the allowable stresses for the separate sleeves' materials; and
σ_g is the geometric mean of the allowable stresses for the separate sleeves' materials.

Figure 1 illustrates the container simplified scheme for mechanical forming material variables and Figure 2 shows this dependence for the case in which all sleeves are made of the same material; because $\sigma_a = \sigma_g = \sigma_{eq}$, this dependence corresponds to Equation (3).

$$K = \frac{r}{R} = \sqrt{\left(1 - \frac{2 \cdot p_{max}}{n \cdot \sigma_{eq}} \right)^n} = \sqrt{\left(1 - \frac{2}{n} (\eta) \right)^n} \qquad (3)$$

Where: $\eta = \frac{p_{max}}{\sigma_{eq}}$ is the coefficient of container capacity and σ_{eq} is the allowable equivalent stress.

Figure 2, shows the relationship between the coefficient of container capacity (p_{max}/σ_{eq}) and the coefficient of the thick wall of any free sleeve (r_i / r_{i+1}). In which the internal pressure of a simple thick-walled cylinder cannot exceed p = 0.5 allowable σ_{eq}, i.e. conventional cylindrical container with only one sleeve do not exceed coefficient of container capacity of 0.5. Due to the dependence between K and η, it is not rational to fabricate simple cylinders with K < 0.25-0.30 and multi-element cylinders with η = 0.20-0.25. In fact, decreasing the value of K from 0.3 to 0.1 (i.e., tripling the outer radius) leads to a 9% increase in the allowable stress. Consequently, the maximum allowable pressure for the simple cylinder (sleeve) barely exceeds p = (0.45-0.47) σ_{eq}. Increasing the number of elements fabricated from the same material (σ_{eq} = const) can significantly increase the pressure.

Figure 1 – Container simplified scheme for mechanical forming variable materials

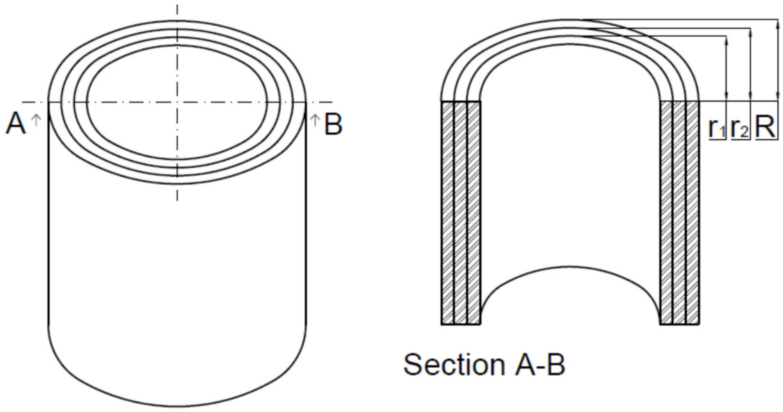
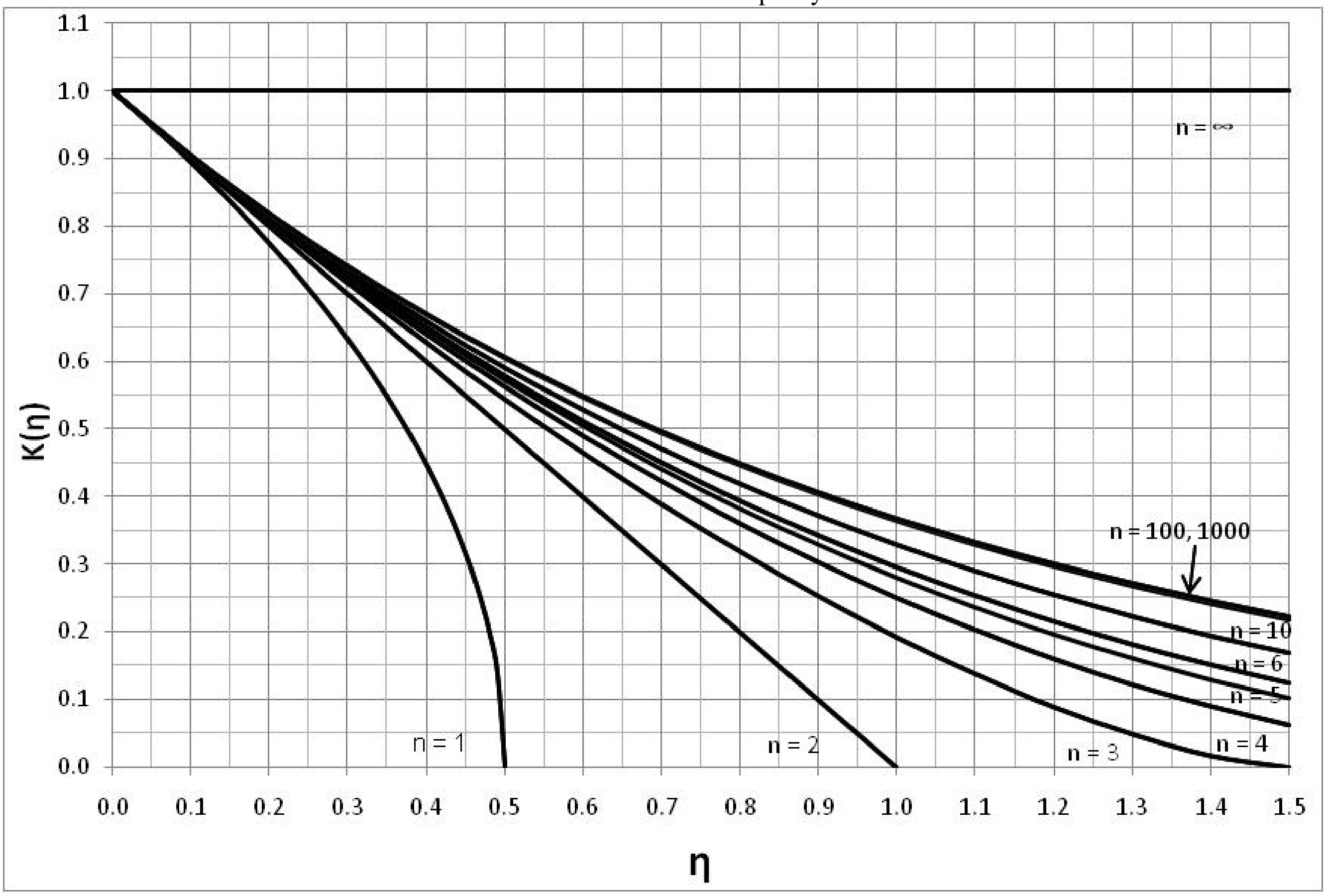


Figure 2 – The relationship among the compound container's dimensions, the number of elements (sleeves), and the coefficient of container capacity



The maximum pressure in a multi-element container is determined by the predicted values of compression stress obtained during the previous assembly and tightening in addition to the allowable stresses σ_{eq}. With the introduction of $v = \sigma_{com}/\sigma_{traç}$, the limit pressure increases according to the Moor's theory:

$$p_{\max} = \left(1 - K^2\right) \cdot \sigma_{eq} \cdot \frac{1 + v}{2} \qquad (4)$$

The coefficient "v" varies from 1 to 2, or $1 \leq v \leq 2$, for high-resistance steel. Figure 2 only presents the graphs for v = 1. The behavior of the curves shows that for a given value of η, the allowable internal pressures in multi-element containers are higher for a greater number of elements.

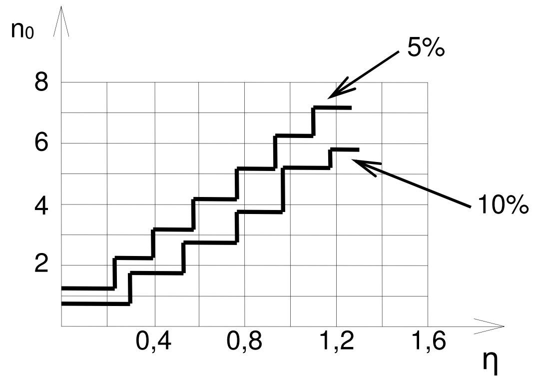
The features shown in Figure 2 show that as the number of sleeves increases, the optimized external radius of the container decreases according to the internal pressure, the material of the sleeve, and the inner radius. However, for containers with a certain number of sleeves, reducing the outer radius is not as significant, and the ever-increasing number n_0 of sleeves becomes unfeasible.

Therefore, the optimal number of sleeves can be determined based on the rationality criterion, which signifies that a decrease in the external radius of the container should be evaluated as a consequence of the addition of more sleeves. The data presented in Figure 3 allow the optimal number of sleeves to be determined for different values of "η" and a rationality criterion ranging from 5 to 10%.

The analysis of the stress state of composite containers for hot extrusion shows that the containers cannot operate safely at pressures greater than 700 MPa when using the industry-available materials.

However, for some branches of industry, containers must have smaller external diameters and the largest possible internal diameters. These characteristics are particularly important for the manufacturing of ceramic parts by compression only, which requires the application of large sleeves that cannot currently be constructed by industry and includes the formation of billets and forging, mechanical, and thermal treatments, as well as high costs. Presented next is another method to solve this problem.

Figure 3 – The relationship between the optimal number of compound container elements and the coefficient of its capacity



3 – NEW CONSTRUCTION THEORY FOR THE COMPOUND CONTAINER

The new container construction consists of a nucleus in the shape of a thin-walled tube that is wound with a thin pre-tensioned ribbon (approximate thickness of 0.5-1.0 mm) until the cylinder can be considered "thick wall" (GUR'EVA, 1978).

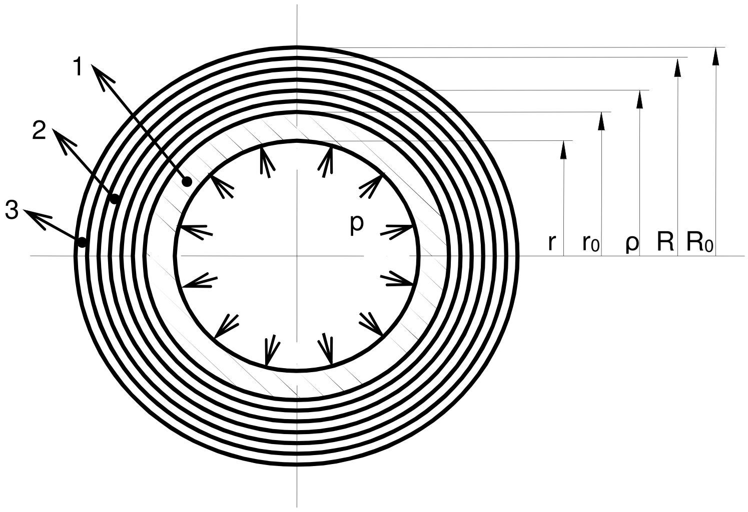
This construction allows for a simpler, faster, and significantly cheaper container fabrication process because there is no need to cast, forge, or temper large billets (up to 100 tons) of high-quality materials to fabricate the external sleeves of the compound containers.

The mechanical properties of the ribbon (yield strength up to 2,500 MPa) are significantly higher than those of steels used for multi-element containers (BOBROVNITCHII and RAMALHO, 2002b), allowing the maximum internal pressures of large-scale containers to increase by up to 1,200 MPa.

The tension of the ribbon during the winding of each layer depends on the desired stress distribution of the container during loading.

For the construction and stress state analysis, the process of winding the ribbon must be understood. Figure 4 shows the layout of the vessel evaluated. Initially, the container consists of a sleeve (1) with a relatively thick wall on which the ribbon of thickness "$d\rho$" is wound (2) for a certain stress "$\sigma_0(\rho)$". Tension is determined as a function of the radius "ρ" of the loop being wrapped and grows until the cylinder obtains a radius "R". Once the cylinder is ready, it is fitted in a shell of radius "R_0". According to what was determined by $\sigma_0(\rho)$, the completed container with internal pressure "p" has stresses equivalent to "$\sigma_y(\rho)$" along its radius "ρ".

Figure 4 – Schematic of the container wrapped with a pre-tensioned ribbon: 1 – internal sleeve, 2 – wound ribbon, and 3 – container shell



On the inner side of the ribbon applied to the surface "ρ_n", consisting of other previously wrapped layers, there is also a stress $\sigma_0(\rho_n)$. The tractive force $\sigma(\rho_n)$ of the same ribbon layer may be decomposed into the following components:

a) Stresses provoked by the application of the same layer:

– Tangential:

$$\sigma_t(\rho_n)_1 = \sigma_0'(\rho_n) \tag{5}$$

– Radial:

$$\sigma_r(\rho_n)_1 = -\sigma_0(\rho_n)\frac{d\rho}{\rho_n} \tag{6}$$

b) Stresses generated from the winding of the external ribbon layers with radius "ρ_n":

– Radial:

$$\sigma_r(\rho_n)_2 = -\frac{\rho_n^2+\rho^2}{\rho_n^2}\int_{\rho_n+d\rho}^{R}\sigma_0(\rho)\frac{\rho\cdot d\rho}{\rho^2-r^2} \tag{7}$$

c) Stresses caused by the applied internal pressure:
– Tangential:

$$\sigma_t(\rho_n)_3 = \rho\frac{r^2}{R^2-r^2}\left(1+\frac{R^2}{\rho_n^2}\right) \tag{8}$$

– Radial:

$$\sigma_r(\rho_n)_3 = \rho\frac{r^2}{R^2-r^2}\left(1-\frac{R^2}{\rho_n^2}\right) \tag{9}$$

According to the third theory of resistance, when the container is subjected to a load from the internal pressure, the equivalent stresses in the layer of radius "ρ_n" can be defined by

$$\sigma_{eq}(\rho) = \sum\left[\sigma_t(\rho_n)-\sigma_r(\rho_n)\right] \tag{10}$$

$$\sigma_{eq}(\rho) = \sigma_0(\rho)\left[1+\frac{d\rho}{\rho}\right]-2\frac{r^2}{\rho^2}\int_{\rho+d\rho}^{R}\sigma_0(\rho)-\frac{\rho(\rho)}{\rho^2-r^2}+\rho\frac{2\cdot r^2\cdot R_0^2}{\rho^2\left(R_0^2-r^2\right)} \tag{11}$$

Neglecting the term "$d\rho/\rho$" and assuming that "$(\rho+d\rho)=\rho$" and $R_0=R$, the second-order Valterra integral equation, which determines the law of tension for the ribbon "$\sigma_0(\rho)$" dependent on the desired distribution of stresses on the wall of the container during loading, "$\sigma_{eq}(\rho)$", can be obtained.

The equation solution, which determines the law of tension during winding, can be written as in Equation (12).

$$\sigma_0(\rho) = \sigma_{eq}(R)\frac{R^2-r^2}{\rho^2-r^2}-2p\frac{r^2}{\rho^2-r^2}-\frac{1}{\rho^2-r^2}\int_{\rho}^{R}\left[2\frac{\sigma_{eq}(\rho)}{\rho}+\frac{d}{d\rho}\sigma_{eq}(\rho)\right]\cdot\left(\rho^2-r^2\right)d\rho \tag{12}$$

Where: $\sigma_{eq}(R)$ is the desired stress on the external layer of the ribbon during the internal pressure loading of the container.

In the simple case, the stresses in each layer are constant along the section, i.e., $\sigma_{eq}(\rho)$ = const = σ; therefore, the Equation (12) is transformed into Equation (13).

$$\sigma_0(\rho)=\sigma\frac{\rho^2-r^2\left(2\ln\left(\rho/R\right)+1\right)}{\rho^2-r^2}-2p\frac{r^2}{\rho^2-r^2} \tag{13}$$

It is interesting to determine the law of tensions at which, under a given internal pressure "p" and a correlation between the selected radii of "r/R", it is ensured that stresses along the section of the container are minimal. Because there are no methods of winding in which compressive stress are generated on the ribbon layer, the minimal strain is "$\sigma_0(\rho) = 0$". For other simple cases of practical application:

$$\sigma_{eq}(\rho)=const \tag{14}$$

The Equation (13) is transformed into Equation (15).

$$\sigma_0(\rho)=2p\frac{r^2}{\rho^2-r^2}\cdot\frac{\rho^2-\rho_0^2+2r\cdot\ln\left(\rho_0/\rho\right)}{\rho_0^2-r^2\left(1+2\cdot\ln\left(\rho_0/R\right)\right)} \tag{15}$$

Under loading, the following stresses appear along the wall of the container:

$$\sigma=2p\frac{\rho^2}{\rho_0^2-r^2\left(1+2\cdot\ln\left(\rho_0/R\right)\right)} \tag{16}$$

Because the core (inner sleeve) must be considered thin-walled, it may be assumed that "$\rho_0 \approx r$". Thus,

$$\sigma_0(\rho)=\frac{p}{-\ln(K)}\left(1+\frac{K_1^2\cdot\ln\left(K_1^2\right)}{1-K_1^2}\right) \tag{17}$$

Where: $K=r/R$ and $K_1=r/\rho$

This dependence may be reasonably estimated by the straight line obtainable by Equation (18).

$$\sigma_0(\rho)=\frac{p}{-\ln(K)}(1-K_1) \tag{18}$$

Thus, during operation, the stress is as in Equation (19).

$$\sigma=\frac{p}{-\ln(K)} \tag{19}$$

From Equation (19), the other parameters of the container can also be obtained, including the allowable pressure limit $p=-\sigma\cdot\ln(K)$ and the coefficient of the optimized thick wall $K=e^{-p/\sigma}$.

The advantage of applying the ribbon or wire to a square section is not significant because the curve relative to n=∞ (Figure 2) is slightly above that for n=5. However, the allowable stress with the thin ribbon is significantly higher than that with the metal sleeve. The yield strength of alloys used in the ribbon manufacturing does not exceed 3,000 MPa. By only taking this information into account, the allowable internal pressure can be at least doubled or the outer diameter of the container can be reduced.

Another advantage of container consolidation by the winding of tensioned ribbon is the ability to manufacture containers with larger internal diameters without the need to manufacture large sleeves by forging (for multi-element containers) or to face difficulties in assembly (large forges). In some cases, the mounting of the wound container can be performed on the site at which it will eventually be utilized.

4 – APPLICATION OF THE DEVELOPED THEORY

This Section presents the development of the container and its development stages.

4.1 Development of a container with four sleeves for a pressure of 2.0 GPa

Using the developed theory, or the relationship of multi-element containers, a device was calculated, designed, and fabricated to generate a high hydrostatic pressure of up to 2.0 GPa (BOBROVNITCHII *et al*., 2006), with a container consisting of four sleeves. For the internal and second sleeves, 4140 steel was selected, while 4130 steel was selected for the third and fourth sleeves. The container was assembled from the inside out; first, the heated second sleeve was installed on the internal sleeve with a previously calculated contact diameter difference. Then, the third sleeve was installed on the pair of sleeves (1 + 2), and this procedure was repeated for the fourth sleeve. Tests on the device showed that the developed theory can accurately select the optimized values for the difference between the diameters that generate tightness between sleeves and evaluate the general mechanical strength of the container. The actual loading conditions of the container, or the area bearing the internal pressure load, are not taken into account by the theory.

4.2 Development stages of the wound container

High-speed steel WV2 was selected for the internal sleeve. The winding ribbon had cross-sectional dimensions of 0.5 by 2.5 mm. It was laminated with a round thread of Mn-Cr alloy; the yield stress of the ribbon reached σ_{esc} = 16,000 MPa, which allowed for a winding tension of 1,400 to 1,500 MPa to be applied.

The winding tension required a force of 190 kg to be applied to the ribbon during winding using the ROMI Tormax 20 device. The device used to apply tension to the ribbon was built without regulating extension strength or safety standards. As the coil diameter increased, the rotational moment of the clamp initially did not allow the projected winding to be defined.

For this reason, the experiments were temporarily interrupted. Then, it was concluded that the containers optimization theory multi-element calculation made it increases the pressure capacity of are mandatory.

CONCLUSIONS

– The multi-element container with an optimized construction is limited to no more than five sleeves;
– The number of elements (sleeves) depends on the capacity of the container, which can be expressed mathematically from the ratio "p/σ_{eq}";
– A container made by the wrapping of thin pre-tensioned ribbon, which is equivalent to a container with an infinite number of elements ($n = \infty$), has a greater capacity for internal pressure loads and is more secure than that without thin pre-tensioned ribbon;
– The most rational use for each industrial construction condition of the multi-element container allows the process parameters under high pressures to increase. In particular, the pressures acting on large containers can increase by up to 1,200 MPa.
– In this way it is possible to improve the quality of processes such as hot and cold extrusion, the cold hydrostatic compression of powders under pressures of up to 2.0 GPa, and the hot compaction of powders in high isostatic pressure (HIP) using container composed of multi-sleeves.

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Nomenclature

K_i	Coefficient of the thick wall of any free sleeve (i)
σ_i	Allowable stress for the material of sleeve (i)
σ_{esc}	Yield strength
σ_a	Arithmetic mean of the allowable stresses for the separate sleeves' materials
σ_g	Geometric mean of the allowable stresses for the separate sleeves' materials
σ_{eq}	Allowable equivalent stress
$p_{\max}$	Maximum pressure
R	Container's external radius
r	Container's internal radius
n	Number of sleeves or rings in the container
n_s	Coefficient of safety
η	Coefficient of container capacity
σ_{com}	Compressive strength
$\sigma_{traç}$	Tensile strength

v	$\sigma_{com}/\sigma_{traç}$
$d\rho$	Ribbon of thickness
$\sigma_0(\rho)$	Strength applied to the outer surface of the ribbon
ρ	Radius ribbon
ρ_n	Inner radio ribbon
$\sigma_0(\rho_n)$	Strength applied to the inner surface of the ribbon
σ_t	Shear strength
σ_r	Radial strength