

# Study of Deformation of Tungsten and Its Alloys for Applications in Fusion Reactors

Catalina Carabajal<sup>1</sup>, Juana Gervasoni<sup>2</sup> and Ariel Fernandez<sup>1</sup>

1. National Technological University, General Pacheco Regional Faculty, Av. Hipólito Yrigoyen 288, B1617 Gral. Pacheco, Provincia de Buenos Aires, Argentina

2. Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, and Instituto Balseiro, Universidad Nacional de Cuyo, 8400 S.C. de Bariloche, Argentina

**Abstract:** This paper focuses on the analysis of properties of tungsten and its alloys, as this is a material employed in the first wall of a fusion reactor. Using different production processes and by adding different impurities to tungsten, new materials can be obtained, with varying physical, chemical and mechanical properties which may help to improve the application to specific situations. In particular, in this work, we investigate the mechanical properties of pure tungsten and tungsten carbide. In both systems, simulated states of metal loading are assessed and collected, using 3D calculation software for metals structures, given the results in terms of deformations.

**Key words:** Metals, tungsten, mechanical properties, fusion.

## 1. Introduction

Due to the current situation of the energy production industry, numerous research and development centres of the world, as well as companies specialized in the subject are looking for possible alternative energy sources [1]. Within these, nuclear energy is a natural candidate, which is considered as a realistic solution to the air pollution produced by other options [2]. In particular, nuclear fusion offers enormous possibilities as a new energy source that could help to meet future needs due to fossil fuel depletion [3]. But achieving the conditions for the operation of nuclear reactors is an extremely complex problem. Within the framework of controlled nuclear fusion studies, the “ITER (International Thermonuclear Experimental Reactor)” is being analysed and developed, under the assumption that it will be the first net fusion energy generator [4].

The main objective of the fusion reactor is to achieve a confinement of the plasma at high

temperatures. The first wall of the fusion chamber is the most complicated device to design in an FIC (Fusion Inertial Confinement) plant [5]. It must fulfil some principal functions: allowing the energy of the driver to efficiently collide with the target and ensuring the survival of it, resisting the repeated emission of X-rays, ions and neutrons that come from the ignition of the target, recovering the conditions for the next shot, and being prepared to support devices that allow the conversion of energy to electricity and provide methods to recover tritium [6].

The most common designs for the reaction chamber have a first wall that resist the radiation emission that reaches it directly, a coating where tritium will be produced and a structure supports the system as a whole. The design of the chamber and that of the target are closely related, because the spectrum of particles that the first wall must overcome depends on the type of target used. In a direct FIC plant, approximately 75% of the energy reaching the first wall is in the form of neutrons, 23% in the form of ions and 2% as X-rays. The greatest short-term risk of

---

**Corresponding author:** Catalina Carabajal, nuclear engineer, research field: nuclear.

the wall is the thermal charge produced by X-rays and ions that deposit all their energy on a thin layer (5  $\mu\text{m}$ ) of the wall, in a very short time interval (less than 1  $\mu\text{s}$ ).

On the other hand, the neutrons deposit their energy in all the volume of the first wall and the mantle, so that they do not produce sudden changes in the thermal charge. The average charge produced by neutrons is similar in both inertial (FIC) and magnetic (FMC) confinement, being the great difference that in the first one the energy tank is pulsed, while it is continuous in the second [7]. In the long range, the risk for the first wall is due to the accumulated neutron damage on the material, which can significantly modify the mechanical properties of the materials that compose it, and make it unusable [8]. For these reasons, the analysis of the mechanical properties in the investigation of the intervening materials in the structure of a fusion reactor is crucial [9].

In particular, a strong candidate to be applied to a fusion reactor is tungsten and their alloys. Tungsten belongs to the group of refractory metals. The binding energy of its atoms is particularly high. They have a high melting point (the highest of the metals of the Periodic Table), low vapour pressure, high modulus of elasticity and good thermal stability. Generally, refractory metals are also characterized by their low coefficient of thermal expansion and their relatively high density [10].

In this frame, tungsten and its alloys are considered to be one of the main candidates to form part of critical pieces such as the divertors in fusion devices, principally due to its properties of magnetic confinement and inertia, its highest melting point (3,420  $^{\circ}\text{C}$ ) and structural strength [10]. Besides, since tungsten has a low activation when it is irradiated, it is considered one of the best materials for high-medium exposure parts of a fusion reactor [11].

In the present work we compare the change in mechanical properties of pure tungsten with carbide tungsten, to analyze which of these materials

are the most suitable to form the first wall of a fusion reactor.

The article is organized as follows: In Section 2 we give a general description of the selected materials and simulation methods, in Section 3 we present and discuss some results, and in Section 4 we discuss some concluding remarks.

## 2. Framework and Description of the Systems

In order to obtain better mechanical properties to apply to different structures of a fusion reactor, we compare pure tungsten (W) and an alloy of tungsten and carbon (CW), since these families of alloys have great resistance to attrition as well as to high temperatures and compression.

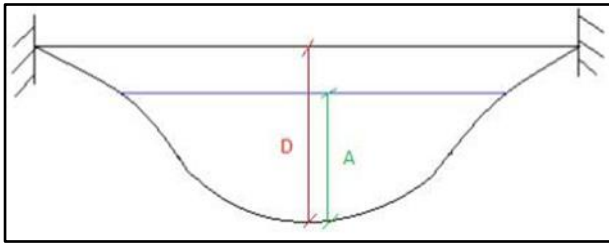
To perform this analysis, a comparative simulation of its mechanical properties is carried out. For both systems, different load states are simulated through the use of calculation software for three-dimensional (3D) metal structures [12].

In the development of the calculations, semi-empirical and phenomenological models are considered.

To perform the corresponding analyses, it is necessary to define the concepts of arrow and displacement.

In Fig. 1 we show the schematic disposition of a double-walled bar. Compression tensions are generated along the axial axis of the bar as a consequence of the deformation that it suffers. The displacement  $D$  is defined as the distance between the axis of the bar and the point furthest from the axis of the bar after deformation. The arrow  $A$  is defined as the distance between the inflection point of the deformation curve and the point furthest from the axis of the bar after deformation [13].

For this case of analysis, double-walled bar of 3 m is simulated. This restriction in the joints implies that the type of deformations is strongly linked to this condition, but it is quite similar to the boundary conditions present in the fusion reactor.



**Fig. 1** Diagram of a double-walled bar, A: arrow and D: displacement.

**Table 1** Tungsten data.

Elasticity module [MPa]	41,000
Poisson's coefficient	0.28
Coefficient of linear thermal expansion (CTE) [m/(m K)]	$4.4 \times 10^{-6}$
Density [g/cm <sup>3</sup> ]	19.3
Specific weight [kN/m <sup>3</sup> ]	0.193

**Table 2** Tungsten Carbide data.

Elasticity module [MPa]	55,000
Poisson's coefficient	0.22
Coefficient of linear thermal expansion (CTE) [m/(m K)]	$4.91 \times 10^{-6}$
Density [g/cm <sup>3</sup> ]	14.95
Specific weight [kN/m <sup>3</sup> ]	0.15

The specifications of tungsten and tungsten Carbide bars, the two elements that we will analyze in the simulations in the next section, are given in Tables 1 and 2.

### 3. Results

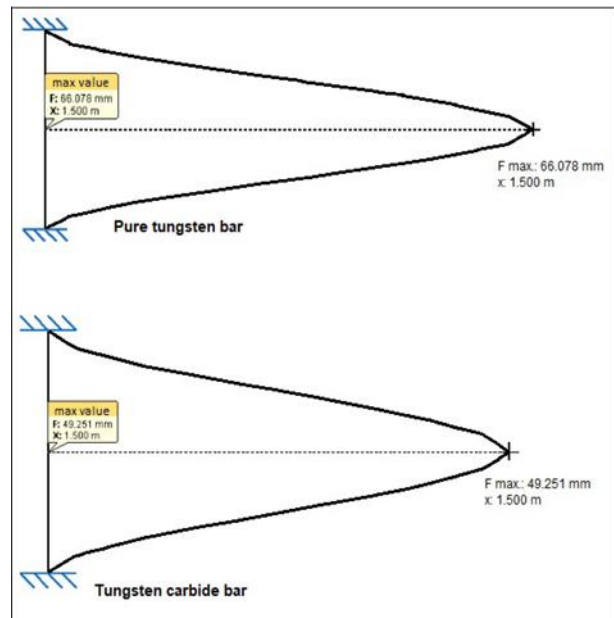
The simulations of the calculations for pure tungsten (W) and tungsten carbide (WC) are done using the software for metal structures CYPE Metal [12].

These models take into account different phenomena and their parameters of diffusion, permeability, absorption, recombination and the release of heat from the reactor wall among others. The results are collected in terms of deformations. Both materials (W and CW) are simulated under linear as well as torque loading conditions, as we show in Figs. 2-5.

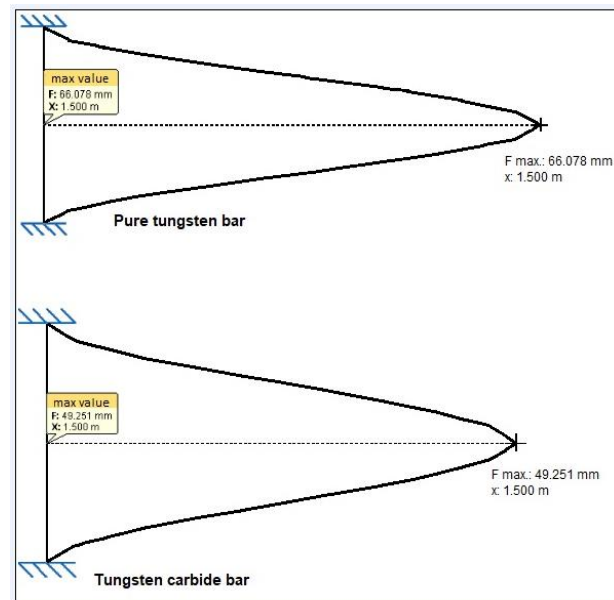
Fig. 2 shows two bars subjected to point linear loads of 100 kN/m applied in the middle of the bar. The upper image corresponds to a pure tungsten bar.

The image below corresponds to a tungsten carbide bar. We observe that, while the pure tungsten bar is banded 66 mm, the tungsten carbide bar is displaced less than 50 mm.

Fig. 3 shows bars subjected to linear loads of 50 kN/m. The upper image corresponds to a pure tungsten bar. The image below corresponds to a tungsten carbide bar. The results are equivalent to the ones shown in Fig. 3.



**Fig. 2** W and CW bars subjected to point loads of 100 kN/m.



**Fig. 3** W and CW bars subjected to point loads of 50 kN/m.

Now, we apply a moment of 50 kN m at half the length (around the axis of each bar). The first image of Fig. 4 corresponds to a pure tungsten bar, and the second image corresponds to a bar of tungsten carbide. If the bars are subjected to moments of 50 kN m, as shown in Fig. 4, applied in the middle of the length (around the axis of the bar), the calculation of the axial tensions, the cut and moment in y and z, the arrow in the x-y plane, the arrow in the x-z plane and total arrow are all equal to zero, as it should be expected from the definition of moments (and it serves to check the simulation).

Regarding the application of torques, Fig. 5 shows the scheme of the moment applied to the bars at half length of them, on an axis perpendicular to the axis of the bar; and Fig. 6 shows the results of the two bars subjected to a torque of 50 kN m applied at half length. We observe that the deformation in the first image, corresponding to a pure tungsten bar, is greater than the deformation shown in the second image that corresponds to a bar of tungsten carbide.

Finally, let us analyze the effect of temperature, applying the same program [12] for the calculation of axial forces for bars subjected to temperature variations. We study the behaviour of these bars in the range of 500 °C and 1,000 °C, which is common in the reactors.

As uniform temperature variations cause linear deformations of contraction or expansion, we apply

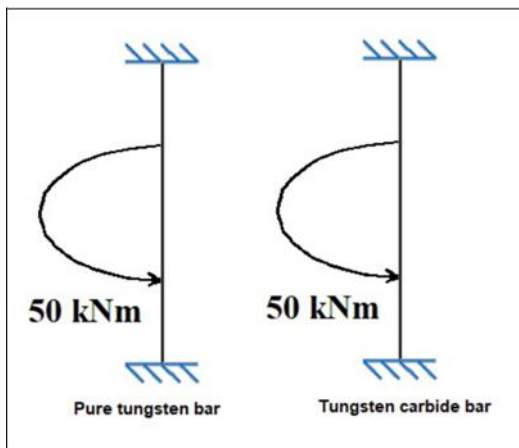


Fig. 4 Diagram of bars subjected to moments applied to the middle of the span (around the axis of the bar) of 50 kN m.

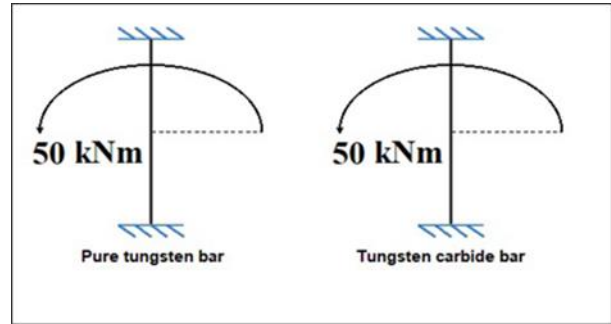


Fig. 5 Diagram of bars subjected to moments applied to the middle of the span (on an axis perpendicular to the axis of the bar) of 50 kN m.

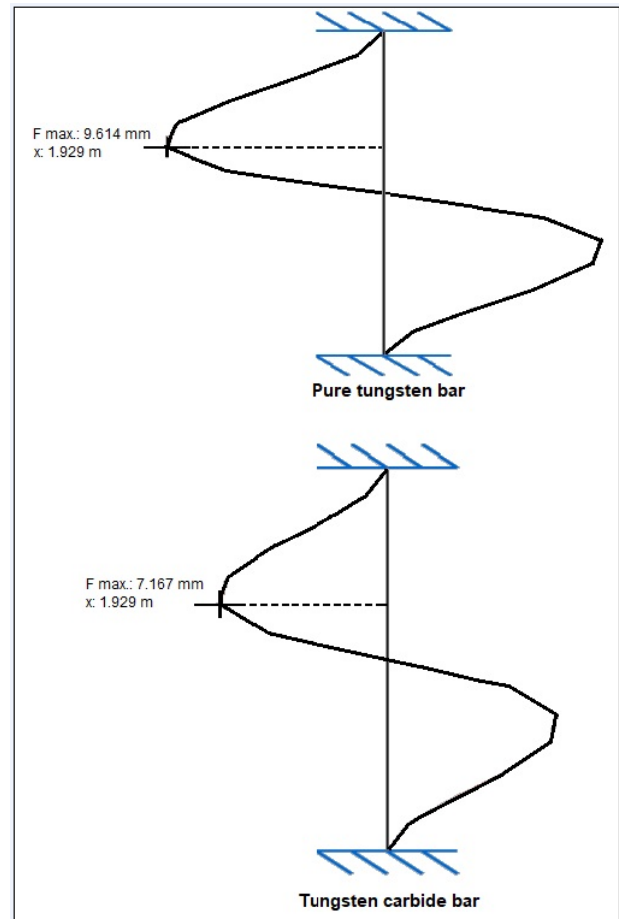


Fig. 6 Bars subjected to 50 kN m moments applied at half length.

axial forces that vary proportionally as a function of the temperature increase. In other words, if the temperature increases twice, the supports or recesses must contain axial forces twice as great as those previously calculated. Thus, it can be observed in the case of pure tungsten, the supports must be able to withstand a force

of 4,100 kN for 1,000 °C, while for a temperature close to 3,420 °C (melting point of pure tungsten), it must withstand a force of 13,940 kN, which is 3.4 times stronger. A similar situation occurs for tungsten carbide. Taking into account its different properties, this behaviour could be due to the fact that the deformation conditions are only linear type.

#### 4. Conclusions and Observations

In this work, simulations were used to collect data to analyse the behaviour of the material in different mechanical situations. We compared mechanical properties of pure tungsten, a candidate material to be applied in the construction of fusion reactors, with carbide of tungsten WC, an alloy composed of the same material. Using our simulations, we found that the elements composed of carbon and tungsten, in different compositions, are more suitable for applications in structures subjected to different stress states than pure tungsten. By changing the type and percentage of the incorporated alloying elements, the properties can be optimized (or aggravated) according to the required application. In particular, we obtained that the carbide of tungsten WC is better than any other composition of carbon and tungsten due to its mechanical, physical and chemical properties, withstanding with less deformation the extreme conditions present on the first wall and critical parts of a fusion reactor.

#### Acknowledgement

This article is partially supported by National University of Cuyo, project C06/C57, Argentina.

#### References

- [1] Daly, H. E. 2006. "Sustaining Our Commonwealth of Nature and Knowledge." *International Journal of Ecodynamics* 1 (3): 236-44.
- [2] Velarde, G., and Minguez, E. 1987. *Emerging Nuclear Energy Systems*. Singapore: World Scientific Publishing Co.
- [3] Clark, R. E. H., and Reiter, D. H. 2005. *Nuclear Fusion Research: Understanding Plasma-Surface Interactions*. Berlin, Germany: Springer-Verlag, p. 481.
- [4] [www.iter.org/mach](http://www.iter.org/mach).
- [5] Valverde, G., Ronen, Y., and Martinez, J. 1993. *Nuclear Fusion by Inertial Confinement*. Boca Raton, FL: CRC Press, p. 751.
- [6] Mehlhorn, T., Cipiti, B. B., Olson, C., and Rochau, G. E. 2008. "Fusion-Fission Hybrids for Nuclear Waste Transmutation: A Synergistic Step between Gen-IV Fission and Fusion Reactors." *Fusion Engineering and Design* 83 (7-9): 948-53.
- [7] Perlado, J. M. 2014. Alfa26, IV, pp. 24-33.
- [8] Hirai, T., Panayotis, S., Barabash, V., Amzallag, C., Escourbiac, F., Durocher, A., Merola, M., Linke, J., Loewenho, T., Pintsuk, G., Wirtz, M., Uytendhouwen, I. 2016. "Use of Tungsten Material for the ITER Divertor." *Nuclear Materials and Energy* 9: 616-22.
- [9] Abernethy, R. G. 2017. "Predicting the Performance of Tungsten in a Fusion Environment: A Literature Review." *Materials Science and Technology* 33 (4): 388-99.
- [10] Lasnner, E., and Schubert, W. D. 1999. *Tungsten: Properties, Chemistry, Technology of the Element, Alloys and Chemical Compounds*. New York: Kluwer Academic.
- [11] Ohr, K., Thompson, R., and Barker, D. 2003. "The Effective Use of Tungsten as a Shielding Material in Nuclear Applications." Presented at the 2003 International ISOE ALARA Symposium, January 15, 2003, Orlando, Florida, USA.
- [12] Cype Metal 3D Program; Software of Calculus for Metallic Structures, 2015.
- [13] Fliess, E. D. 1971. *Estabilidad*, Vol. 2. Argentina: Kapeluz.