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DEVELOPMENT OF HIGH PRESSURE TORSION DEVICE INTEGRATED BY THE TRANSMISSION SYSTEM REMOVABLE ADAPTED TO A 200T COMPRESSION TESTING MACHINE

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Abstract. *Acquisition of laboratory testing equipment might be expensive for an academic institution or a company. Therefore, this article presents the project of High Pressure Torsion (HPT) testing equipment adapted to 200T capacity compression testing machine; the project is developed in 3D CAD software virtual environment. In short, HPT is a Severe Plastic Deformation (SPD) material forming technique. HPT processing is considered the most effective SPD technique in terms of reducing the crystallographic grain size down to nanometer level. Generally speaking, during the HPT processing, a small cylindrical sample of polycrystalline material is simultaneously submitted to compressive and torsional stress without fracture due to plastic deformation. The designing methodology of the equipment takes into account main technical parameters required during the sample processing, like torque, hydrostatic pressure, sample diameter, and material types. To dimension the components of the project, the analytical methods and finite element analysis based on theory of machine elements were employed. One of the fundamental features of the proposed HPT equipment is that the twisting moment applied to the specimen is transmitted using spur gear train. A movement system with linear guides is used to remove the projected components from the compression testing machine, thus allowing performing two different tests in the same equipment.*

Keywords: *Severe Plastic Deformation (SPD); High Pressure Torsion (HPT); Mechanical Project of HPT Equipment.*

1. INTRODUCTION

Material processing techniques known as SPD are in their essence experimental procedures of polycrystalline material mechanical forming with a fundamental feature of imposing a very large plastic strain on the specimen without occurrence of fracture. In this case, no significant change is observed in the overall dimensions of the workpiece. SPD techniques allow achieving excellent results in the crystallographic grain refinement of the material structure. Given the average size of the obtained grains, these materials are classified as bulk Ultrafine-Grained (UFG) materials. The grain sizes of UFG materials can reach the nanoscale range, below 100nm. (Valiev et al., 2006).

The research developed using SPD experimental techniques is of great interest for the industry of components manufactured by superplastic forming method, since for this manufacturing method the fine-grained materials are considered the most appropriate. Zhilyaev and Langdom (2008) indicate that the degree of superplastic deformation in elevated temperatures and mechanical strength increase in fine-grained materials.

SPD techniques most commonly encountered in literature are Equal-Channel Angular Pressing (ECAP) and High Pressure Torsion (HPT) techniques. Among all SPD techniques, HPT processing of the material allows obtaining the smallest crystallographic grain size.

Nevertheless, the project of HPT equipment itself does not necessary require a significant financial investment. The HPT process basically requires a combined action of compressive and torsional loading; and to achieve this, additional equipment can be adapted to already existing laboratory machines, e.g. to the hydraulic press.

1.1 HPT Technique

The fundamental principles of HPT processing are based on the works of Bridgman (1943). However, the key features of HPT as they are known today, as well as the scientific interest to this technique, developed only in the second half of the 1980s (Zhilyaev and Langdom, 2008).

Figure 1 illustrates the principle of HPT technique; a metallic sample in the shape of a disk is placed between two anvils and simultaneously subjected to compressive and torsional loading. In short, the extensive compressive load in the given equipment geometry causes a significant hydrostatic pressure, and when one of the anvils is rotated, high plastic torsional straining is achieved without fracturing the sample.

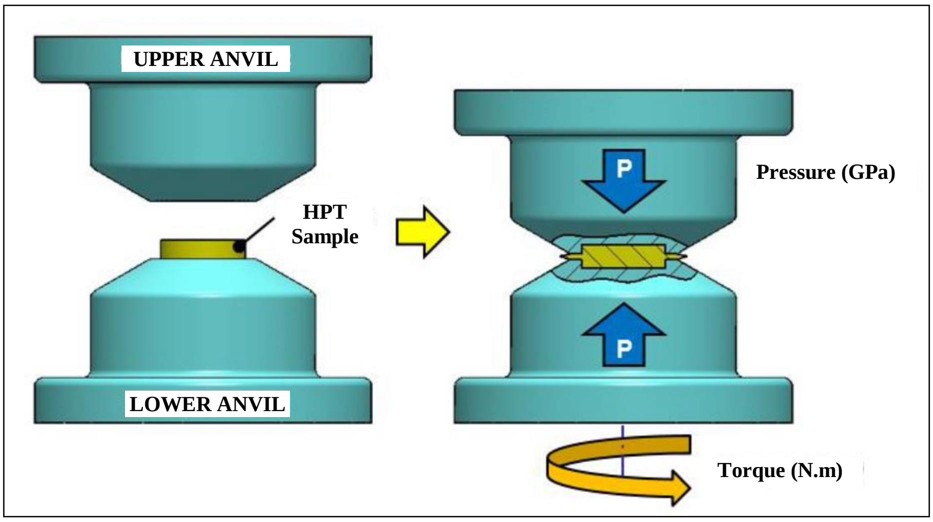

Figure 1. Schematic illustration of basic HPT processing principle
Available from: Ferreira (2017) (inspired by Kawasaki et al. (2011), p. 309)

Torsional and compressive loading force magnitudes required in HPT equipment are, among other parameters, closely related with the dimensions of the sample. Hohenwarter et al. (2009) mention that one of the greatest limitations of HPT processing is the size of the sample, because with the increase of the sample diameter, a higher experimental equipment capacity is required, and larger equipment might require high costs.

Generally, the specimens for HPT are around 1.0 mm thick with the diameter of about 10 mm. HPT technique is used for polycrystalline materials, like pure metals, or copper (Cu), iron (Fe), nickel (Ni), aluminum (Al), titanium (Ti), and other alloys. The processing can be done either at room or at increased temperatures. The rotation speed of the lower anvil may vary between 1.0 to 2.0 rpm.

The applied hydrostatic pressure and torque are among most important parameters in HPT processing. The required hydrostatic pressure depends on the material of the sample and may vary between 1.0 to 10.0 GPa. Hohenwarter et al. (2009) argue that as a rule of thumb, to avoid the relative sliding of the sample between the anvils the applied hydrostatic pressure should be at least three times the yield stress of the sample material. The torque applied in HPT should be high enough to cause simple shear plastic deformation of the workpiece.

One of HPT processing purposes is grain refinement of the material. According to Calado (2012), HPT allows obtaining materials with nanosized grains, more precisely with grain size below 50nm. However, presently existing technology does not allow achieving such UFG materials on a large industrial scale.

To measure the degree of shear deformation imposed on the sample the term equivalent strain is used in HPT. With increasing number of rotations applied to the specimen, the absolute values of equivalent strain also increase and generally reach maximal values in the range of ε=16 - 32 (Hohenwarter et al., 2009).

Despite the excellent results obtained by HPT processing, the main drawback of this technique is a small sample size. Hohenwarter et al. (2009) mention that HPT processing of a 40 mm diameter cylindrical workpiece would require an equipment with loading capacity of 400 T and applied torque of 13 000 Nm. According to Zehetbauer and Zhu (2009), processing of a specimen with the diameter of 100 mm requires a 40 000 kN load.

Basically, the HPT equipment consists of two mechanical systems for transmitting the torsional and compression loading, respectively. In the project of the HPT equipment developed by Margiela and Neyt (2013), the outlined loading capacity and applied torque were 780 kN and 883 Nm, respectively.

2. MATERIALS AND METHODS

Figure 2 shows the 200 T compression testing machine (Alfred J. Amsler & Co.®) for building materials used in this project of HPT equipment. The compression machine is in its essence a hydraulic press consisting of a high capacity hydraulic cylinder with adjustable hydraulic force, and an adaptable system of wheel-driven power screw for securing the testing sample.

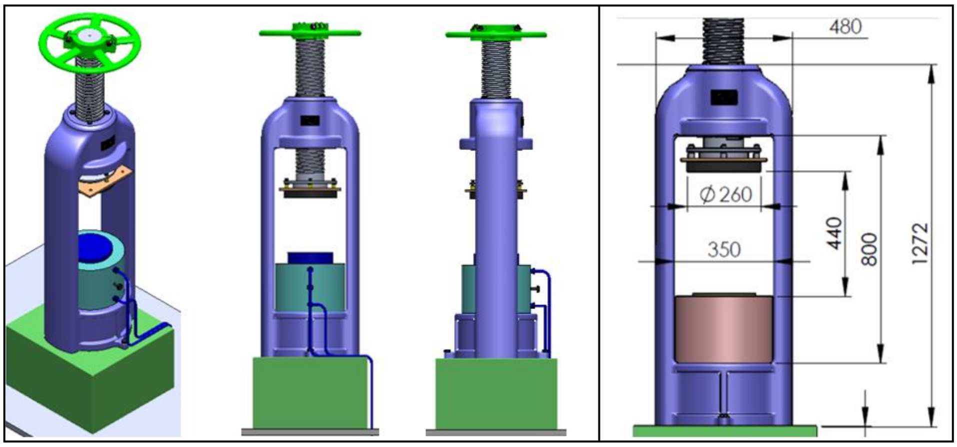

Figure 2. Schematic illustration of compression testing machine in various views with main dimensions in mm
Available from: Ferreira (2017)

The required torque value was obtained employing the theory of inelastic torsion available in Hibbeler (2010) and Garcia et al. (2015); the same fundamental principles were applied in the works of Margiela and Neyt (2013). According to this theory, the torque necessary for processing of the cylindrical specimen can be obtained as follows Eq (1).

$$M_t = 2\pi\tau_u \int_0^{D/2} \rho^2 d\rho \tag{1}$$

In the equation above M_t is the torque, π is the mathematical constant, τ_u is the ultimate shear stress, D is the diameter's sample and ρ is the radius' sample.

In summary, the following values were used in the current project of the HPT equipment for processing of the specimens at room temperature: maximal applied torque Mt=3600 Nm, hydrostatic pressure from P = 1.0 to 8.0 GPa, diameter of the specimens from 8.0 to 50 mm, and maximal rotation speed 1.5rpm.

The analytical dimensioning of the machine elements was based on the literature data for mechanical project of the components. There is a vast number of works available that set standards to the dimensions and specification of machine elements, e.g. Norton (2013), Budynas and Nisbett (2011), Melconiam (2009), Juvinall and Marshek (2008), and Provenza (1990).

The numerical analysis was performed employing the finite element method (FEM) using Solid Works Simulation® (Dassault Systèmes SolidWorks Corporation, Vélizy-Villacoublay, France). Reaction forces on bearings and shafts were determined using Ftool® (PUC-Rio, Rio de Janeiro, Brazil). Specification of the roller bearings was based on the data provided in the bearing manufacturer SKF® (Gothenburg, Sweden) catalogue.

The internal dimensions of the compression machine were the limiting factor for maximal dimensions of such components as output gear and thrust bearing.

Using the defined dimensions of the mechanical components for the HPT equipment, the 3D project of this equipment was developed in Solid Works®.

Taking into account that the same equipment is intended for use in two different types of experiments, the linear guides for removing the transmission system were installed. Thereby, the components of the HPT device can be easily removed from the compression machine and the equipment can be employed both for compression and HPT testing.

3. RESULTS AND DISCUSSION

The development of an HPT test equipment (high-pressure torsion) adapted to a machine compression test was initially proposed by Ferreira *et. al.* (2016). In that way the transmission system and other parts was designed to be assembled stationary in the compression testing machine which was enable only to perform tests of HPT technique. Therefore, the compression tests themselves was disabled to that proposed design.

In the present work, the calculation of the design parameters of the device was concluded, mainly the removable transmission system assembly. The referred device design is completely detailed in the Master Thesis of Ferreira (2017).

3.1 Spur gear transmission system

Figure 3 shows the spur gear drive assembly for HPT device consisting of 2 pairs of gears configured into a compound gear train. The suggested material for the gears is AISI 4340 nitrided steel.

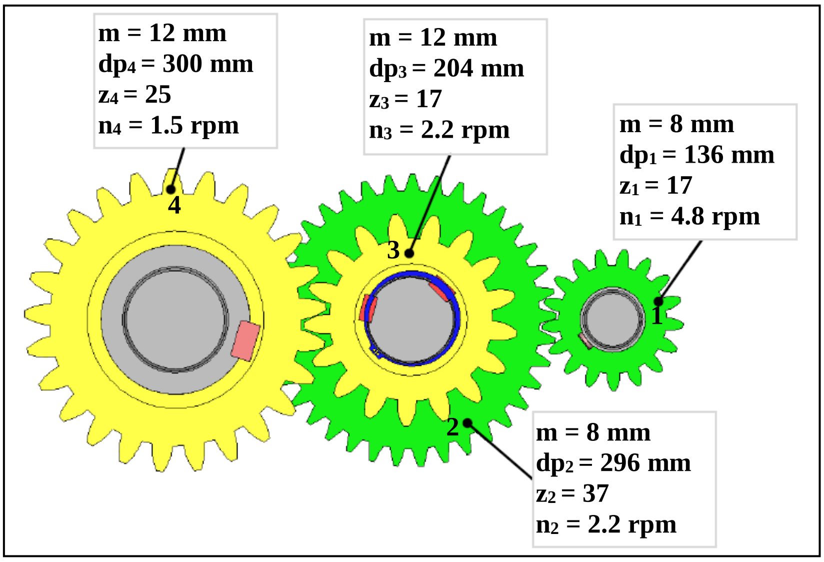

Figure 3. General information on transmission system gears
Available from: Ferreira (2017)

According to Melconiam (2009), if the drive-driven gear pair is made of the same material, it is sufficient to dimension only the pinion, since if a pinion withstands the stress, the driven gear efficiently withstands it too.

For pinions 1 and 3, the computed minimal number of teeth is z = 17. Since the pitch diameter of gear 4 should be smaller than dp = 300 mm, the 3 and 4 gear ratio is limited. Table 1 summarizes the main variables for pinion 3, considering the thickness of the gear equal to b = 70mm.

Table 1. The main variables computed for pinion 3 at 70 mm thickness

m(mm)	d_{pp}(mm)	i	σ_f(MPa)	σ_c (MPa)	S_f	S_h
8.0	136	2.21	208	1177	2.37	1.12
10.0	170	1.76	166	1093	2.97	1.30
12.0	204	1.47	138	1033	3.56	1.46
16.0	238	1.10	104	953	4.75	1.71

Considering bending (Sf) and contact (Sh) safety factors associated with the gear ratio "i", the best metric module for pinion 3 is m = 12.0 mm.

Table 2 demonstrates the variables determined for pinion 1. In this case the satisfactory results were obtained for module equal to 8.0 mm.

Table 2. The main variables computed for pinion 1 at 70 mm thickness

m(mm)	d_{p1}(mm)	i	σ_f(MPa)	σ_c (MPa)	S_f	S_h
8.0	136	2.18	132	980	3.51	1.58
10.0	170	1.76	114	902	4.16	1.88
12.0	204	1.37	95	853	5.07	2.11

Given the obtained results for the gears, the global ratio for the compound gear train is approximately 1:3.1.

3.2 Gearmotor selection

The necessary power of the gearmotor for the HPT device project was estimated at 565 W. The required parameters for the input shaft of the gear train transmission system are rotation speed equal to n = 4.8 rpm and maximal torque Mt=1125 Nm. Considering the equipment layout, a parallel-shaft helical gear gearmotor with hollow shaft was found suitable. Thus, the selected model, FAF 77R37 manufactured by Sew Eurodrive® (Bruchsal, Germany). This model has output torque capacity and rotation speed Mt = 1140 Nm and n = 5.8 rpm, respectively; the nominal power is Pw = 750 W.

To control the rotation speed and torque applied on the HPT specimen, a frequency controller and encoder connected to the gearmotor system need to be installed.

3.3 Validation of the transmission system shafts

Figure 4 shows some technical parameters of the shafts that compose the transmission system of the HPT device.

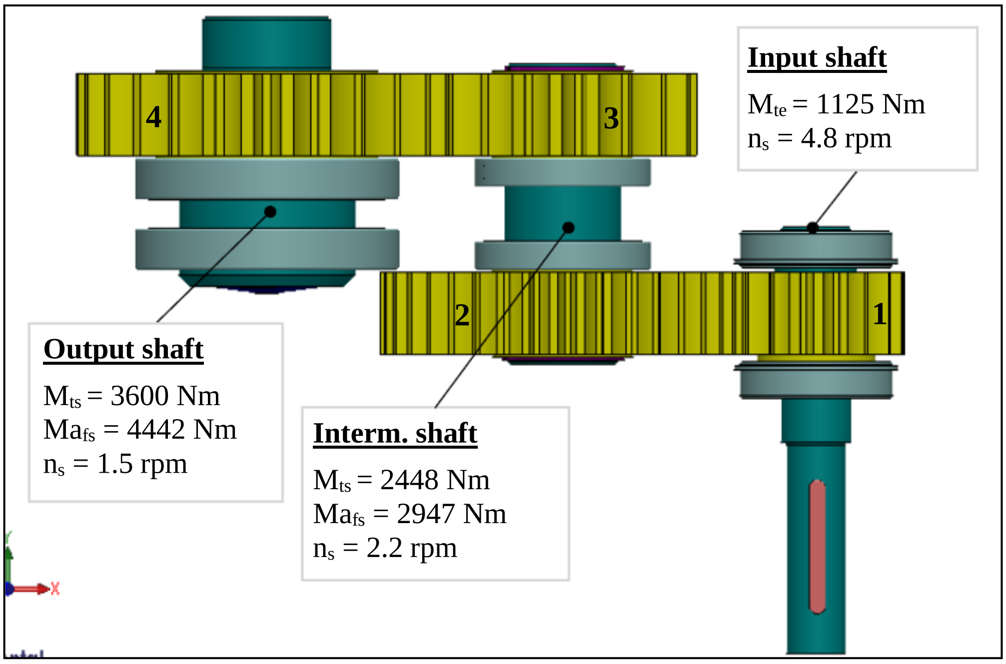

Figure 4. Schematic illustration of the general information about the HPT device shafts
Available from: Ferreira (2017)

The fatigue safety factor of the designed shafts is Nf = 2.5, and effective stress concentration factor is kf = 1.60 at key section. The upper anvil shall be suited with an internal cavity; therefore, the output shaft was designed based on the mechanical properties of the nitrided steel AISI 4340. The intermediate shaft was projected based on the properties of the AISI 1040 steel. According to the rules for automated design, designing of the input shaft was not necessary.

In this manner, the minimal required diameter of output and intermediate shafts, computed on the basis of the equation established by ASME standard considering zero alternating bending stress and constant bending moment, was approximately d = 90 mm.

3.4 Selection of roller bearings

To withstand a high axial loading equal to F = 2000 kN, a thrust bearing shall be specified. Due to a possibility of misalignment on the output shaft, a self-aligning spherical roller thrust bearing was chosen.

Given the thrust bearing housing diameter on the output shaft and the internal space limits of the compression machine, the selected spherical roller thrust bearing is 29422 E. The computed static safety factor for this bearing is equal to S0 = 1.50. The service life for this bearing at rotation speed in the range of 1.0 rpm is 2773 h. Therefore, life value of this bearing can be considered reasonable, as rotation speed and frequency of use of the HPT equipment are low.

The single row deep groove radial bearings were chosen due to their high capacity of withstanding the radial loads and low cost. For the input and intermediate shaft the selected bearings were 6312N and 6020, respectively; for the output shaft the 6030 bearing was selected.

The selection of these bearings and their housings is not considered critical, since they are mounted in a paired configuration and are subjected to purely radial loading, showing a bearing life above 100E+06 millions of rotations at slow rotation speed.

3.5 Lower anvil bracket

Figure 5 shows the lower anvil bracket, which houses the anvil and constrains the rotational movement transmitted by the output shaft. This assembly is connected to the transmission system structure by cylindrical threaded rods and hex nuts.

Shear pins, axially moving into the guide bushes, prevent transmission of the torque to the hydraulic cylinder.

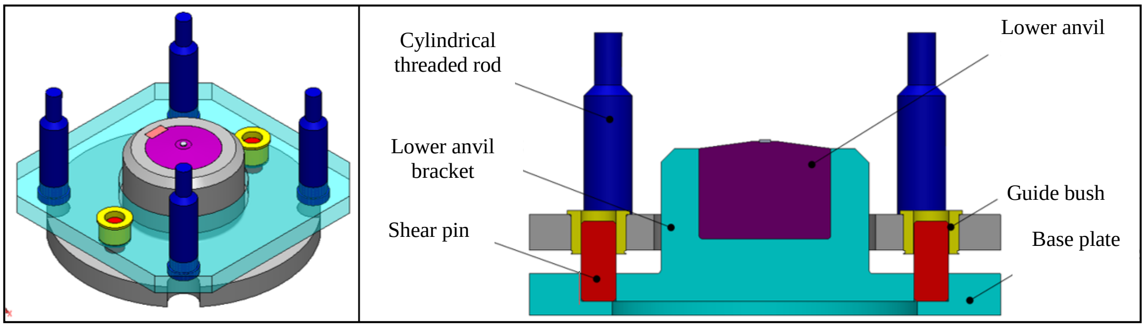

Figure 5. Schematic illustration of the lower anvil assembly.
Available from: Ferreira (2017)

Maximal individual shear stress values for the pin and the threaded rod are τ_(máx)= 81 MPa and τmáx =48 MPa, respectively. The material chosen for these components is AISI 1040 steel. The safety factor is FS=3.0.

3.6 The transmission system frame

The components of the transmission system (the gears, shafts, bearings, gearmotor, etc.) are supported by highly rigid thick metal sheet chassis, called the transmission system frame. Figure 6 shows this frame with the guide brackets, which permit the translational movement of the whole assembly.

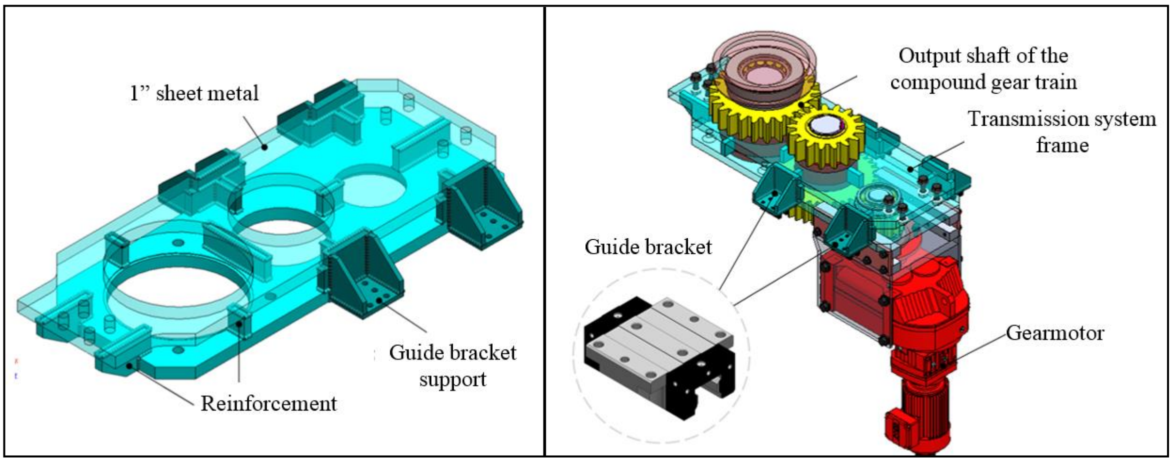

Figure 6. Schematic illustration of the transmission system frame.
Available from: Ferreira (2017)

Figure 7 shows the mechanical components arranged on the input and intermediate shafts of the transmission system.

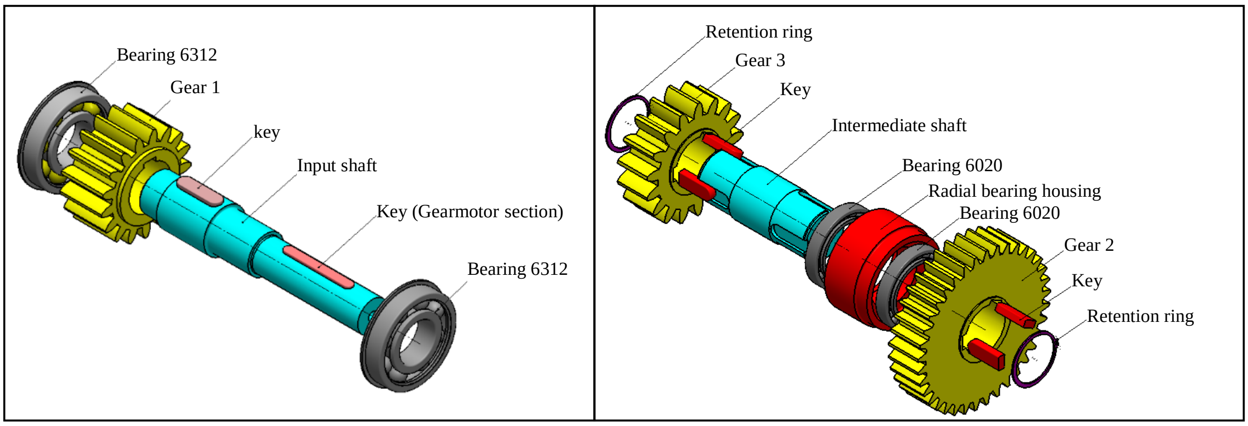

Figure 7. Schematic illustration of the input shaft (a) and intermediate shaft (b) components
Available from: Ferreira (2017)

Figure 8 demonstrates the arrangement of the mechanical components on the output shaft.

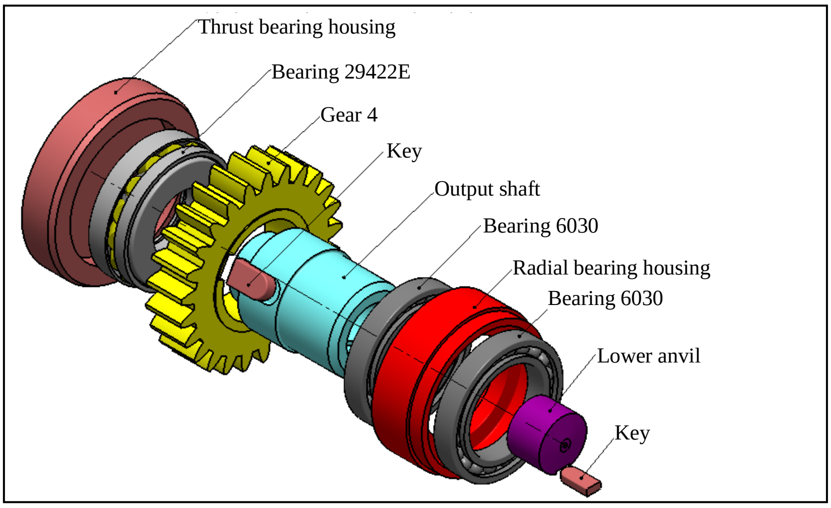

Figure 8. Schematic illustration of the output shaft components
Available from: Ferreira (2017)

3.7 Layout of the HPT equipment

The components of the HPT equipment shall not interfere with the functioning of the compression testing machine. Therefore, the transmission system frame is mounted separately on the square metallic structure with the profiled rails. For the HPT procedures, the transmission system shall be fixed to the metallic beam structure using hex bolts; during the compression tests the transmission system shall be removed.

Figure 9 shows installation of the transmission system of the HPT equipment employing the liner guides.

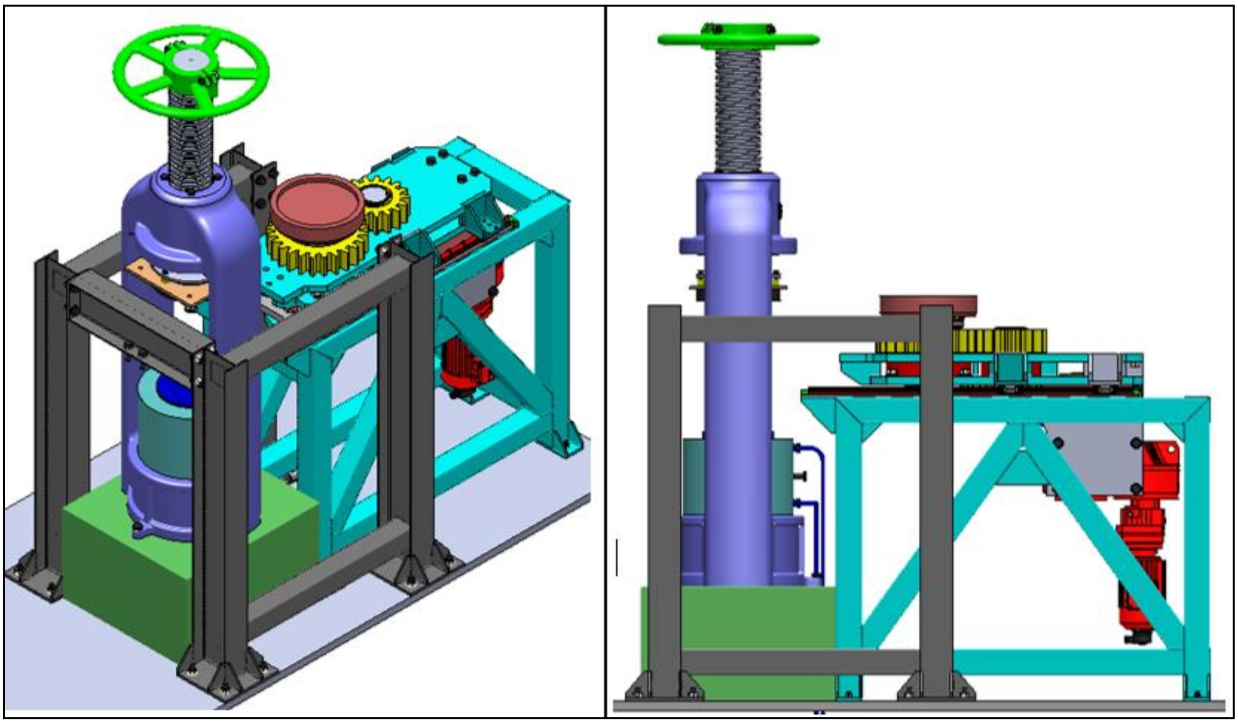

Figure 9. Installation of the transmission system on the linear guide system.
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Figure 10 presents the overall layout of the HPT equipment.

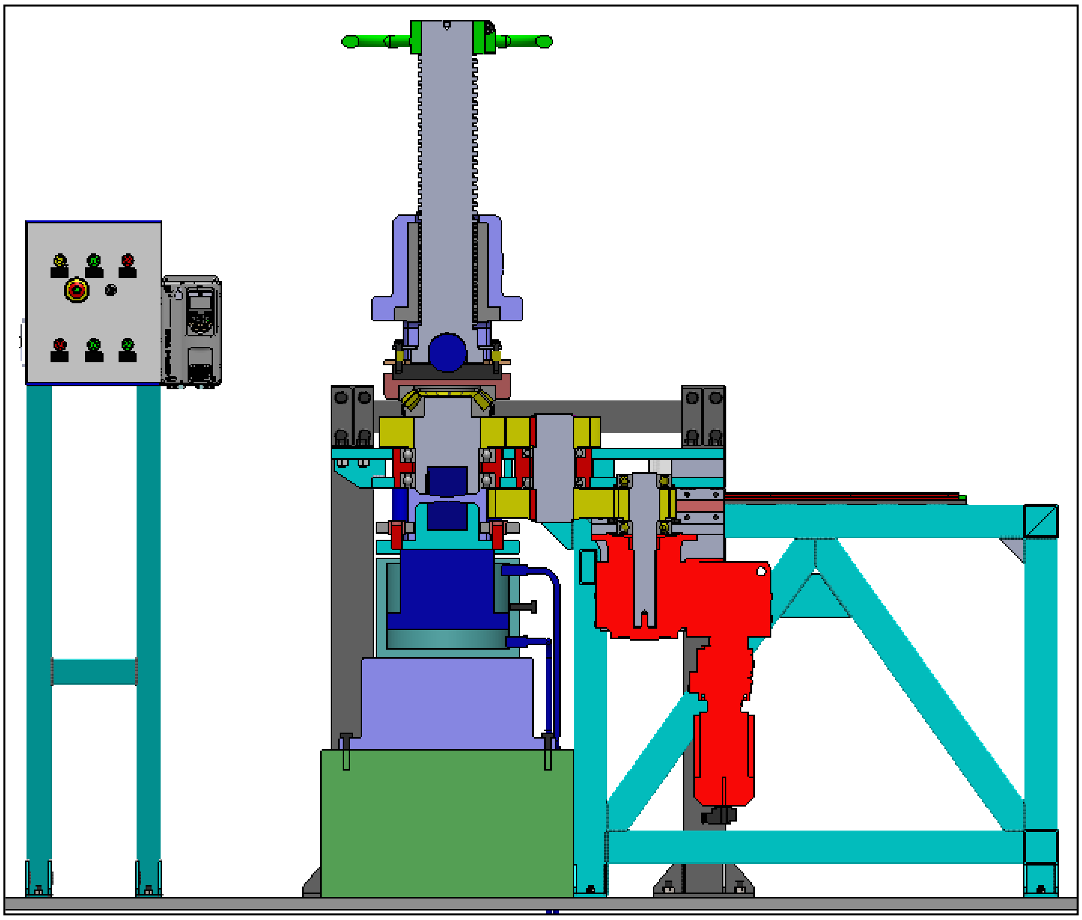

Figure 10. Cross section of the HPT equipment layout
Available from: Ferreira (2017)

4. CONCLUSIONS

A high capacity compression testing machine (200 T) allows processing of the specimens with larger diameters. The proposed equipment project would permit processing the workpieces of 50 mm diameter, which is a significant improvement comparing to the diameters found in the literature (10 mm).

Employment of already available compression testing machine for HPT processing is an excellent option, which allows decreasing the HPT equipment costs for the laboratory.

The dimensioning and specification of the components that compose the HPT device suit the needs defined for this equipment.

Development of the HPT equipment amplifies the possibilities of the scientific research, since HPT processing is a recent technique, and many students and academic professionals are not yet familiarized with it.

The design and layout of the HPT equipment allow mounting and dismounting it easily, therefore two different testing procedures are possible on the same machine.

5. ACKNOWLEDGEMENTS

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