Applied Computer Science, vol. 17, no. 3, pp. 92–105
doi: 10.23743/acs-2021-24

Submitted: 2021-08-23 | Revised: 2021-09-17 | Accepted: 2021-09-28

tensile strength, FEM, CAD modelling, stainless steel, mechanical engineering

Mateusz SAWA [0000-0002-9800-7715]*, *Mirosław SZALA* [0000-0003-1059-8854]**, *Weronika HENZLER* [0000-0002-9388-1382] *

INNOVATIVE DEVICE FOR TENSILE STRENGTH TESTING OF WELDED JOINTS: 3D MODELLING, FEM SIMULATION AND EXPERIMENTAL VALIDATION OF TEST RIG – A CASE STUDY

Abstract

This work shows a case study into 3D modelling, numerical simulations, and preliminary research of self-designed test rig dedicated for uniaxial tensile testing using pillar press. Innovative device was CAD modelled, FEM optimized, build-up according to the technological documentations. Then, the device utilization for tensile testing was validated via preliminary research. 3D model of the device was designed and FEM-analyzed using Solid Edge 2020 software. The set of FEM simulations for device components made of structural steel and stainless steel and at a workload equal 20 kN were conducted. This made it possible to optimize dimensions and selection of material used for individual parts of the device structure. Elaborated technical documentation allows for a build-up of a device prototype which was fixed into the pillar press. After that, the comparative preliminary experiments regarding tensile strength tests of X5CrNi18-10 (AISI 304) specimens were carried out. Tests were done using the commercial tensile strength machine and obtained results were compared with those received from an invented device. The ultimate tensile strength of X5CrNi18-10 steel, estimated using the commercial device (634 MPa) and results obtained from the patented device (620 MPa), were in the range of the standardized values. Findings confirm the utilization of the invented device for tensile strength testing.

1. INTRODUCTION

Tensile strength testing is the fundamental method for the evaluation of the basic mechanical properties of structural materials. Operation idea of testing machines, i.e. instruments used to state the strength of materials, is well known. The specimen of tested material shall be subjected to stresses leading to its deformation; values of forces and

* Lublin University Of Technology, Mechanical Engineering Faculty, Department of Materials Engineering, Students Research Group of Materials Technology, Nadbystrzycka 36, 20-618 Lublin, Poland, mateusz.sawa1@pollub.edu.pl, weronika.henzler@pollub.edu.pl
** Lublin University Of Technology, Mechanical Engineering Faculty, Department of Materials Engineering, Nadbystrzycka 36, 20-618 Lublin, Poland, m.szala@pollub.edu.pl

deformation are measured. Typically, a universal testing machine (UTM) is used to investigate mainly the tensile strength and compressive strength of materials. Thus, different research papers relate to estimating the mechanical properties based on true stress analysis during tensile, likewise (Estrada et al., 2019; Kowal & Szala, 2020; Żebrowski et al., 2019) or compression (Machrowska et al., 2020; Szala et al., 2020). Moreover, the specialized testing machines allow to an investigation of the fatigue properties of materials (Branco et al., 2021; Macek, Szala, Trembacz, Branco & Costa, 2020), however then advanced equipment is required. Wide variety of metallic materials, e.g. carbon (Świć et al., 2020), structural (Caban, Nieoczym & Gardyński, 2021), high strength (Macek, Branco, Trembacz, Costa, Ferreira & Capela, 2020) steels, aluminium (Kilicaslan, Elburni & Akgul, 2021), magnesium (Zagórski et al., 2019), nickel (Sarre et al., 2016), cobalt (Szala, Chocyk, Skic, Kamiński, Macek & Turek, 2021), titanium (Rudawska et al., 2019) based alloys are employed in mechanically loaded components and structures fabrication. In addition, welded (Nowacki, Sajek & Matkowski, 2016), riveted (Lubas & Witek, 2021) or adhesive (Kłonica, 2018) joints are required to be mechanically investigated too. The available studies show that testing of mechanical properties of materials is a source of highly useful knowledge allowing the correct selection of materials or forecast the structure performance. Engineering practice requires cost-effective and easy-in-operation equipment for preliminary, in-work investigation of as-fabricated welded samples. Standard mechanical testing procedures aiming at the estimation of the metallic specimens strength properties employes complex testing systems. Moreover, specimens could be redirected to professional laboratories. An easy-in-use rig for mechanical testing of welded joins could speed up the modification of welding procedures before the final welding technology qualification. This will limit the production time and reduces the costs. Therefore, the objective of the current project was to invent the test rig for tensile testing of welded joints using simple, workhouse equipment.

Nowadays essential engineering practice is to optimize the mechanical behaviour of engineering structures using FEM (finite elements method) analysis's which is systematically employed by many research groups (Falkowicz, Ferdynus & Wysmulski, 2015; Kawecki & Podgórski, 2017; Szklarek & Gajewski, 2020). Moreover, recommended research practice is to validate the FEM results experimentally (Dziubińska et al., 2021; Jonak, Karpiński & Wójcik, 2021; Różyło, Wysmulski & Falkowicz, 2017). On the other hand, in the specific application, the in-situ mechanical tests are still essential and cannot be replaced by computer simulations. Exemplary, to evaluate the quality of welded joints especially during qualification of the welding technology (Janeczek, Tomków & Fydrych, 2021). It is known from the ISO 6892-1 standard that UTMs allow determining the complex set of mechanical properties e.g. ultimate tensile strength R_m, yield strength $Rp_{0.2}$ (set at 0.2% plastic strain), elongation used for engineering strain and stress calculations. In case of the welded specimens testing, according to the standard EN ISO 4136, the most important is to evaluate the ultimate tensile strength (R_m) deriving from the maximum load (F) and the cross-sectional area of the specimen. It seems that Rm could be easily estimated with the usage of basic engineering equipped able to measure the applied force, likewise hydraulic presses. In addition, the engineering-workhouses the hydraulic presses are much more popular than the tensile testing divides mostly because these are quite universal machines. Therefore, rather than utilizing the expensive specialized equipment, it seems justified to elaborate ergonomic, cost-effective devices for tensile testing by adapting the available equipment. Therefore there is need form the point of view of industry practice to elaborate easy-tooperate device for tensile testing of metallic samples. This device should base on utilization popular equipment and well-available workhouse equipment likewise pillar hydraulic press. Presses have a wide applications in machine building industry, and facilite fast determination of the maximum load required to strength calculation.

Patent databases survey indicates that no devices are allowing tensile strength testing using a hydraulic press. In other words, specimen tensile via semi-compression. An exemplary patented device (Lyalin Mikhajlovich, Zykov Mikhajlovich & Sidorov Aleksandrovich, 2021) consists of a movable housing with a fixed-grip unit for fixing one end of the sample. Inside the mobile housing of the device, there is a fixed part with a second grip unit attached to secure the other end of the sample, fixed to the fixed anvil. Hitting the upper surface of the moving part, it is dynamically vertically moving downwards while breaking the sample, fixed on one side in the fixed holder and on the other side in the moving holder. This device allows the impact test to be carried out for samples using an available strength machine. Another available description of the patent application (Pezowicz et al., 2016) shows a device for biaxial stretching of biological samples. It is characterized by the use of four jaws for fixing the sample, embedded in sleds connected to the corresponding drive systems. Each jaw can move perpendicular to the direction of movement of the sleds, which allows generating the expected lengthening of the sample according to the tensile axes. It is also known for its utility model (Haizhou, 2020) testing machine for tensile strength of samples. It consists of a bracket, a screw drive system, guide rods, lifting bolts, lifting plate, top plate, two jaw assemblies, pressure sensor, notched guard, and protective cover. The device can carry out a static sample tensile test by attaching the sample to the jaws and by straining it with vertical force.

Basing on the literature and patent databases survey it can be concluded that tensile strength tests are very often carried out using specialized equipment or complex UTM systems. These rigs, contrary to the popular pillar hydraulic presses, are often inaccessible, economically problematic due to their cost-demanding maintenance.

Therefore our project aims to research the design of the device for tensile testing of metallic samples with the usage of a pillar hydraulic press. The application of CAD modelling, FEM optimization allows the design of the original device structure. The utilization of the built test rig was positively validated by preliminary investigations.

2. CAD MODELLING OF THE INVENTED DEVICE

Brief foredesign. The project aimed to create a device for static, sample tensile testing to be carried out with the use of a laboratory hydraulic press P-50 type. The tested specimen should be loaded uniaxially and the device should be easy to use. The main problem was to achieve a sample shoulder system eliminating the non-linearity which could be presented while testing the welded joint specimens. The device should allow tensile testing of metallic samples in standardized conditions described by (*ISO 6892-1: Metallic materials – Tensile testing – Part 1: Method of test at room temperature*, 2010) and (*ISO 4136:2012 Destructive tests on welds in metallic materials — Transverse tensile test*, 2012, p. 2012).

Invented device characterization. The original idea of the device was 3D modelled using Solid Edge 2020 software. The designed facility is presented with the markings of the individual parts in Fig. 1. The device consists of a housing (1) which consists of a lower base

(1.1), two side walls (1.2) perpendicular to it, a rear wall (1.3) fixed between the sidewalls (1.2) and attached to the sidewalls (1.2), and the top plate (1.4) with a through-hole (A) in the central part parallel to the bottom plate (1.1). On the top plate (1.4) with a hole (A) in the central part, a graded mounting sleeve (2) with a thrust bearing (3) attached to it, is mounted in the axis of the bore (A), in which the upper part of the upper jaw assembly (4) located in the hole (A) in the top plate where the first end of the test sample (10) is mounted. In the top plate (1.4), there are two through-holes (B) arranged symmetrically to the axis of the hole (A). In the axis of each of the two holes (B), a guide sleeve (5) facing upwards is attached and in each of the two holes (B), there is a rod (6), the upper end of which is attached to the upper movable plate (7) above the top plate (1.4). On the other hand, the lower end of each rod (6) is attached to the lower movable plate (8) inside the housing (1). A lower jaw assembly (9) is attached to the lower movable plate (8) from the bottom base side.

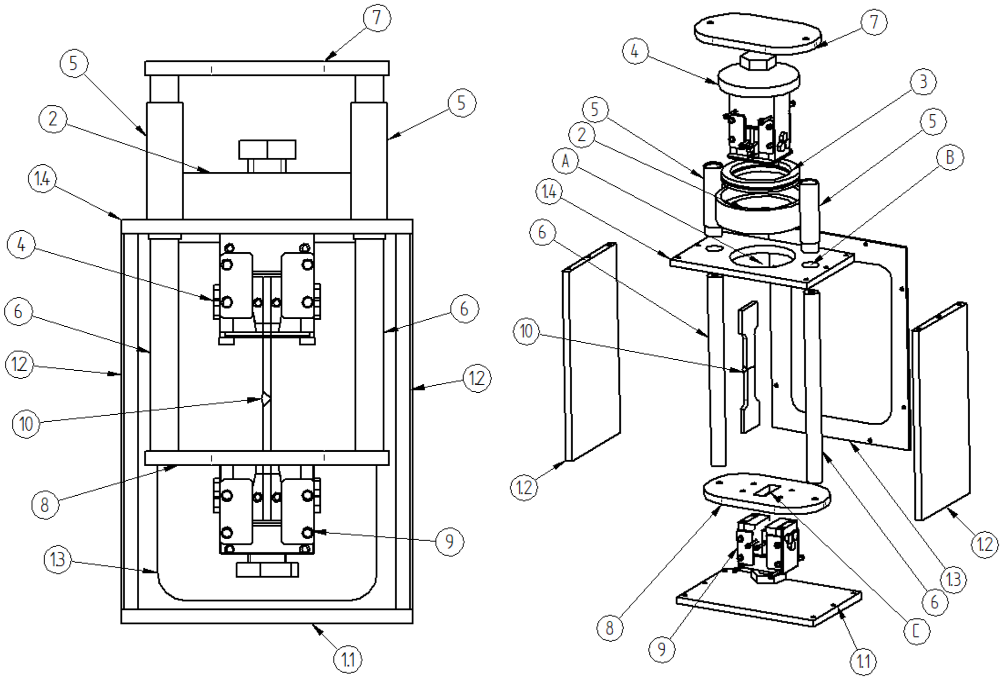

Fig. 1. Patented idea of the device (CAD) – description in the text

In the examination of the samples using a device, the sample shall be fixed in the jaw assemblies in such a way that the jaw-grabbing surface is clamped on the grip surface of the sample, which is achieved by using a screw to press the jaw gripper to the grip surface of the sample. The device with the sample fixed shall be placed on the press table and the clearance between the upper surface of the upper movable plate and the application surface of the press rod shall be eliminated. Then, through a press rod, pressure is exerted on the upper movable plate, which, by interacting with the rods, causes the lower movable plate to move, causing the sample to stretch. On the other hand, the upper part of the sample is attached to the top plate of the housing, which prevents it from moving progressively.

The main advantage of the invention is the use of a thrust bearing on which the upper assembly is mounted. The bearing, which is aligned with the geometry, compensates for the non-linearity of the sample stretching by positioning the jaws spontaneously under the applied force. This is crucial while testing the welded joints which are prone to heat-induced deformation and other dimensional and shape-related non-uniformities. The device idea was subject is an objective of a patent application submitted to the Patent Office of the Republic of Poland (Szala, Sawa & Walczak, 2021).

3. STRUCTURE OPTIMISATION – FEM SIMULATION

The device structure was optimized using Solid Edge 2020 software. For the designed device, a static analysis of the stresses caused by the working load needed to break the sample of F=20 kN was performed. The accuracy of the calculation mesh was 3.25 mm. The set of analyses allows selection of the ideal structural material, and to minimalize the total mas and in turn, optimize the performance of the invented device.

Each of the FEM simulations allows determining the strengthened components. Then the rig was redesigned to improve the mechanical properties of the strenuous areas. Finally, the FEM analysis was repeated to validate the redesigned object. FEM results of the finally designed device are presented in Fig. 2–Fig. 5. The graphical results of the endurance simulation of the whole device with a fixed sample are shown in Fig. 2. Stress distribution of housing and movable part of the device is shown in Fig. 3. The deformation of construction is shown in Fig. 4. Even though the rig will be dedicated to testing the welded joints the isotropic sample was designed for the FEM analysis and preliminary research. The results of sample stress distribution and its dimensions are shown in Fig. 5. On the stress scale, critical stresses are determined for the device material, i.e. structural steel S355 and stainless steel X5CrNi18-10 (AISI 304), EN 1.4301 according to (*EN 10088-2:2014 – Stainless steels. Part 2: Technical delivery conditions for sheet/plate and strip for general purposes*, 2014). The same specimen's shape was manufactured for the preliminary in-situ experiments.

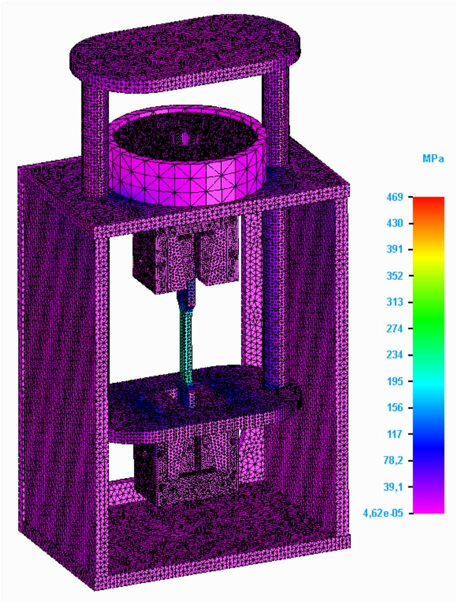

Fig. 2. Graphic results of FEM simulation of stresses estimated for a device in operation conditions

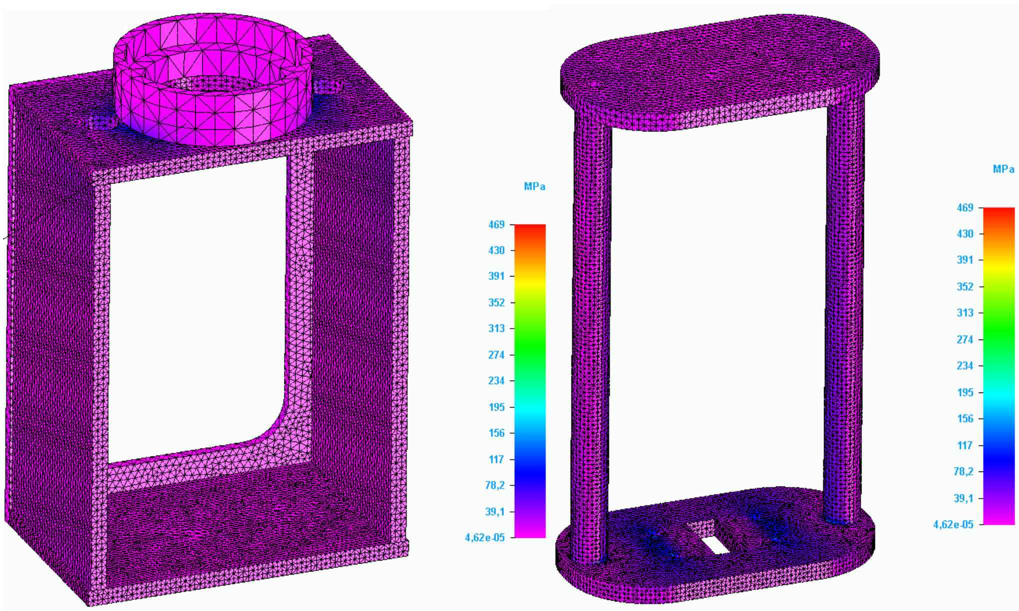

Fig. 3. From left: tension in housing and movable part – FEM

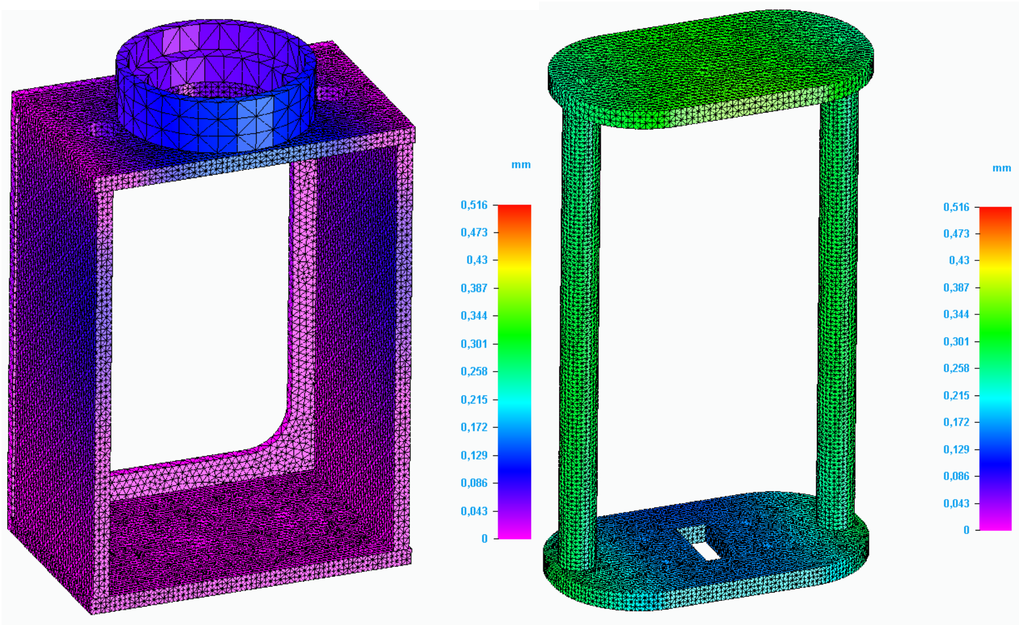

Fig. 4. Deformation of – from left: housing, movable part – FEM

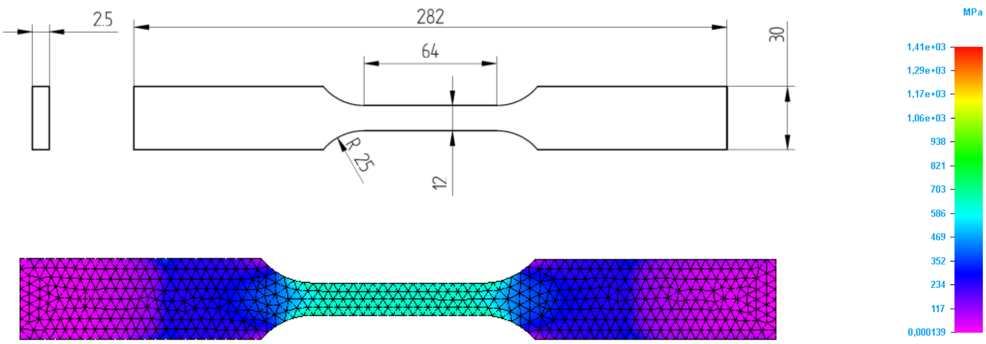

Fig. 5. The dimensions of a test sample with a square section along the gauge length and results of FEM simulation presenting stresses distribution in the specimen

4. BUILT-UP DEVICE AND VALIDATION OF INVENTION

The results of FEM analysis allow obtain the final design, select the materials and optimise dimensions of structural details described in the technological documentation. After that, the test device components were manufactured and the test rig dedicated for tensile testing was finally constructed. In addition, the device operation idea was subject to a patent application submitted to the Patent Office of the Republic of Poland (Szala, Sawa & Walczak, 2021). Finally, the designed device was manufactured, as can be seen in Fig. 6. In order to demonstrate the utility of a proposed patent and evaluate the usefulness for real-operation of the build-up test device, preliminary research was carried out.

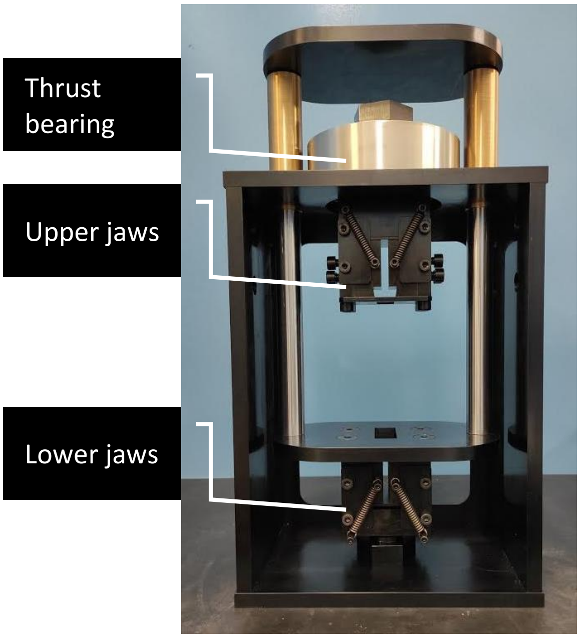

Fig. 6. Invented device for tensile testing

4.1. Preliminary research procedures and tested samples characterization

The main goal was to compare the ultimate tensile strength result obtained from the originally designed test rig, presented in Fig. 7a, and the commercial tensile machine, Fig. 7b. Even though the device is dedicated for welded joints tensile in the preliminary studies we utilized samples fabricated from a model material, namely stainless steel grade X5CrNi18-10 (AISI 304). This steel thanks to its good comprehensive mechanical properties, good ductility and weldability (Pańcikiewicz et al., 2020; Skowrońska et al., 2021; Zheng et al., 2018) is utilized in broad types of applications likewise leisure (Szala & Łukasik, 2018), engineering piping systems (Łabanowski et al., 2017), and devices operating in a corrosive environment (Ha et al., 2018) also operated under tensile loads (Hamidah, Wati & Hamdani, 2018). As shown in Fig. 8, steel microstructure consists of austenite with the visible twinning due to sheet metal forming which is in agreement with the literature (Szala et al., 2019; Zheng et al., 2018). Nominal mechanical properties of tested stainless steel are given in Tab. 1. Samples used for comparative tensile testing were water-jet cut for the 2.5 mm thick sheet metal to be strengthened along to the X5CrNi18-10 sheet metal rolling direction. The dimensions of test specimens and exemplary samples are shown in, Fig. 5. The ultimate tensile strength (UTS, R_m) of a set of identical samples was tested using the INSTRON 8801 commercial machine (a maximum available load of 100 kN) and with a hydraulic press (a maximum load of 500 kN) equipped with the constructed device, both shown in Fig. 7. The displacement and load were controlled during investigations. Therefore, UTS (estimated as maximum stress that a material can withstand while being stretched) and elongation were calculated according to ISO 6892-1 standard specification. The fractured X5CrNi18-10 steel specimens were comparatively analyzed concerning the standard mechanical properties and literature.

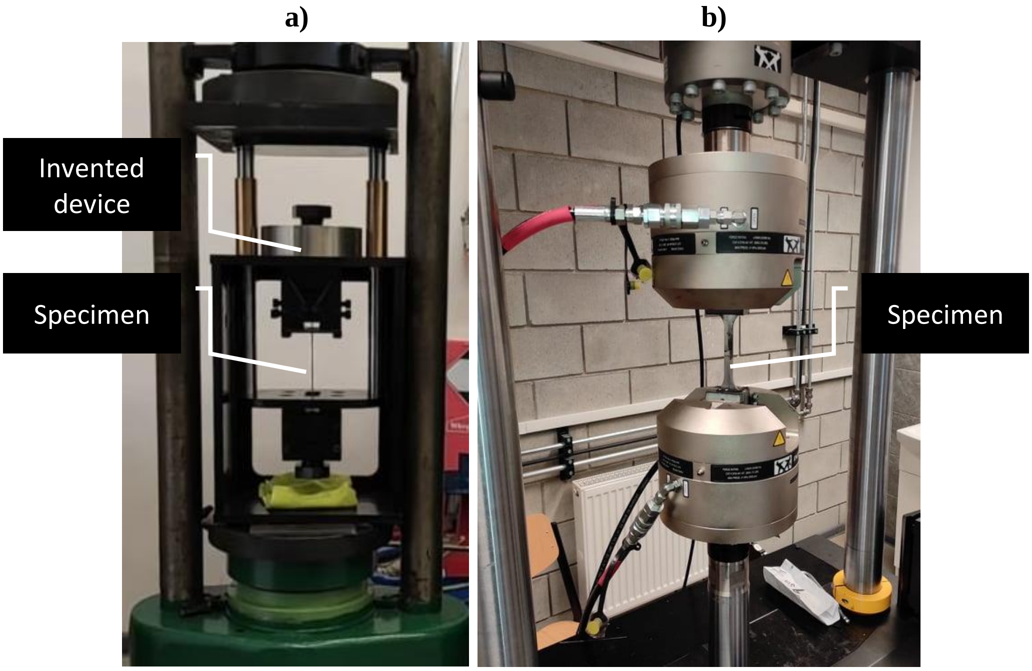

Fig. 7. Equipment used for preliminary tests: a) hydraulics press with an invented device, b) universal testing machine INSTRON 8801

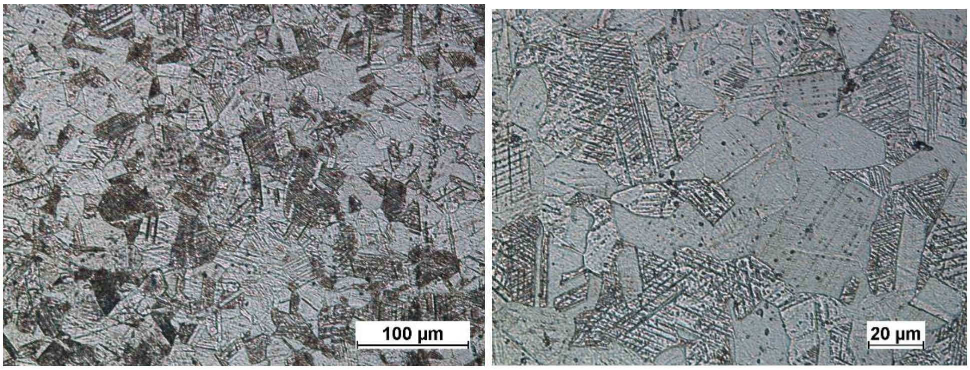

Fig. 8. Microstructure of the X5CrNi18-10 (AISI 304) stainless steel, metallographic microscope

Tab. 1. Mechanical properties of X5CrNi18-10 samples according to (*EN 10088-2:2014—Stainless steels. Part 2: Technical delivery conditions for sheet/plate and strip for general purposes*, 2014)

Ultimate tensile strength, R_m	0.2% proof strength, $R_{p0.2}$	Elongation after fracture		Vickers hardness*
		A_{80}<3 mm thick, $\%_{min}$	A≥3 mm thick, $\%_{min}$	192±12 HV0.2
540-750 MPa	230 MPa	45%	45%	

* measured according to the ISO 6507 standard

4.2. Results and analysis of the utility of the invented device

The exemplary AISI 304 tensile sample is shown in Fig. 9 while Tab. 2 and Fig. 10 present the quantitative results of the comparative tensile testing. The fracture is located in the highest stress area which agrees with the FEM simulations presented in Fig. 5. The fractographic inspection of the broken samples reveals the ductile fracture mode which is in agreement with the literature data for cold-rolled AISI 304 austenitic stainless steel (Amininejad, Jamaati & Hosseinipour, 2019). Moreover, fractured samples were characterised by relatively high elongation after fracture at the level of 50–60% (see Fig. 8), which also follows the elongation required by the standard recommendations, see Tab. 1. The literature (Nedeloni et al., 2018) reports the ultimate tensile strength (UTS) of X5CrNi18-10 at the level of R_m= 605 MPa. The comparison of maximum tensile stress and UTS indicates comparable results given for both the invented device and the professional testing machine, see Fig. 10. Results fulfil the required nominal mechanical properties of X5CrNi18-10 steel. Also, it should be pointed out that AISI 304 steel mechanical properties strongly relates to the grain size (Mahmood et al., 2021, p. 304) namely, grain refinement increases the strength and hardness. Moreover, the AISI 304 steel sheet rolling direction affects the anisotropy in tensile properties (Rout, 2020) - higher UTS value is obtained usually on the specimen tested along the rolling direction than transverse tensile.

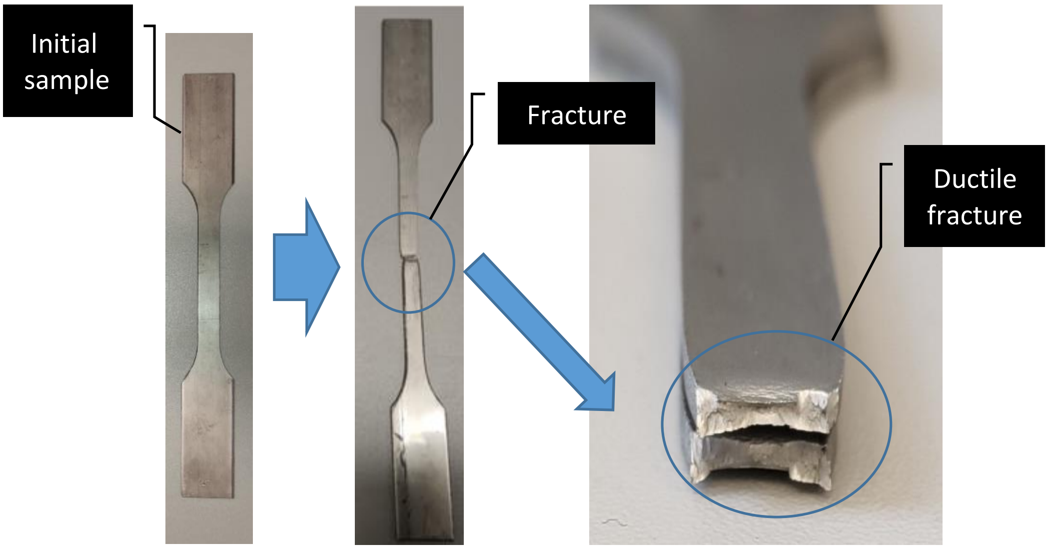

Fig. 9. AISI 304 tensile sample: fracture locations, marked ductile fracture, specimen dimensions in fig. 5

Tab. 2. Test results of X5CrNi18-10 stainless steel specimens

Type of test rig used for tensile testing	Maximum stress, F_m [N]	Ultimate tensile strength, R_m [MPa]
INSTRON 8801	19341	634
Invented device fixed in hydraulic press P-50 type	19530	620

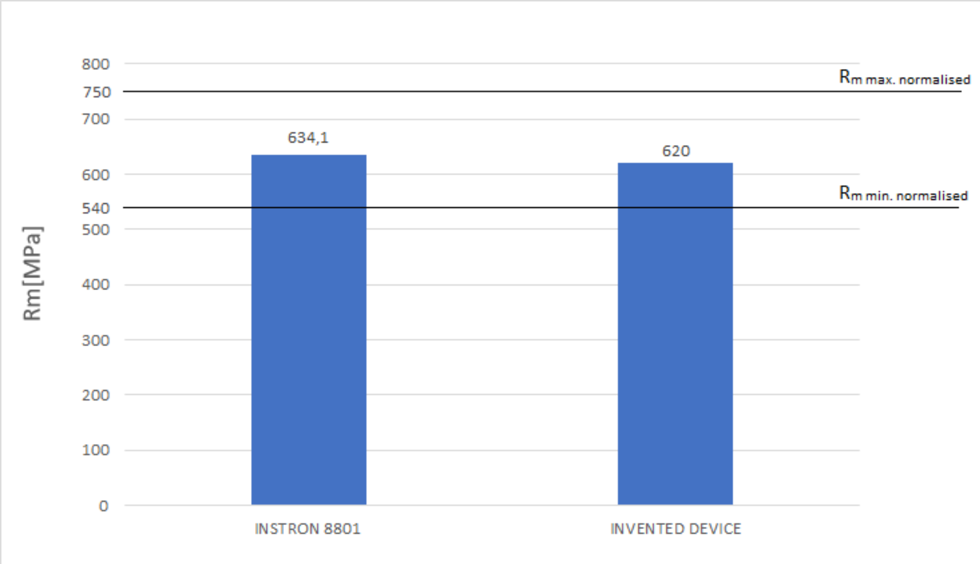

Fig. 10. Comparison of ultimate tensile strength obtained from the commercial machine, a self-made device with nominal values given for X5CrNi18-10 steel acc. to EN ISO 10088-2 standard (*EN 10088-2:2014 – Stainless steels. Part 2: Technical delivery conditions for sheet/plate and strip for general purposes*, 2014)

Findings obtained in comparative tensile testing studies, using two test rigs, confirm the utilization of the invented and constructed test device for testing the R_m of steel samples. The innovation of the device relies on the application of thrust bearing allows positioning the loaded jaws uniaxially, which is crucial in the case of welded joints testing. The R_m of model samples made of X5CrNi18-10 steel were at a comparable level and follow the literature data and standard requirements. Obtained results confirm the thesis of the project. Tensile testing using the hydraulic press provides reliable results and gives comparable to professional test equipment results.

5. CONCLUSIONS

The results of the case study lead to the following conclusions:

– The original device for tensile testing of metallic samples with the usage of pillar hydraulic press was invented. Thanks to the application of computer modelling and FEM simulation, device design optimization was achieved.
– The innovation of the device relies on the application of thrust bearing allows compensating the non-linearity of the stretching welded samples by positioning the loaded jaws uniaxially. The device idea is an objective of the patent application submitted to the Patent Office of the Republic of Poland (Szala, Sawa, et al., 2021).
– The utilization of the built test rig for ultimate tensile strength (UTS) testing was positively validated by the preliminary experimental investigations using model X5CrNi18-10 stainless steel specimens.

– Ultimate tensile strength of X5CrNi18-10 steel specimens, estimated using the commercial device (634 MPa) and obtained from the patented device (620 MPa), were in the range of the standardized values. Fractographic inspection of the specimens reveals the ductile fracture mode.
– The beneficial effect of the designed device is the possibility of stretching the test samples, including welded joints with the help of a press (e.g. in workshop conditions), which can translate into positive economic effects such as avoiding the need to purchase specialized testing strength machines.

Acknowledgement

This project was financed by the Lublin University of Technology Project – Regional Initiative of Excellence from the Ministry of Science and Higher Education on the basis of contract No. 030/RID/2018/19 and within the framework of the statutory activities of the Students Research Group of Materials Technology (Mechanical Engineering Faculty, Lublin University of Technology, Poland).

The authors would like to send their gratitude's to Conti Sp. z.o.o company (Rzeszów, Poland) for the manufacturing of the invented device according to supplied technological documentation.

REFERENCES

Amininejad, A., Jamaati, R., & Hosseinipour, S. J. (2019). Achieving superior strength and high ductility in AISI 304 austenitic stainless steel via asymmetric cold rolling. *Materials Science and Engineering: A*, *767*, 138433. https://doi.org/10.1016/j.msea.2019.138433

Branco, R., Costa, J. D., Martins Ferreira, J. A., Capela, C., Antunes, F. V., & Macek, W. (2021). Multiaxial fatigue behaviour of maraging steel produced by selective laser melting. *Materials & Design*, *201*, 109469. https://doi.org/10.1016/j.matdes.2021.109469

Caban, J., Nieoczym, A., & Gardyński, L. (2021). Strength analysis of a container semi-truck frame. *Engineering Failure Analysis*, *127*, 105487. https://doi.org/10.1016/j.engfailanal.2021.105487

Dziubińska, A., Surdacki, P., Winiarski, G., Bulzak, T., Majerski, K., & Piasta, M. (2021). Analysis of the New Forming Process of Medical Screws with a Cylindrical Head of 316 LVM Steel. *Materials*, *14*(4), 710. https://doi.org/10.3390/ma14040710

EN 10088-2:2014 – Stainless steels. Part 2: Technical delivery conditions for sheet/plate and strip for general purposes. (2014). ISO.

Estrada, Q., Szwedowicz, D., Vergara, J., Solis, J., Paredes, M., Wiebe, L., & Silva, J. (2019). Numerical simulations of sandwich structures under lateral compression. *Applied Computer Science*, *15*(2), 31–41. https://doi.org/10.23743/acs-2019-11

Falkowicz, K., Ferdynus, M., & Wysmulski, P. (2015). FEM analysis of critical loads plate with cut-out. *Applied Computer Science*, *11*(2), 43-49.

Ha, H.-Y., Jang, J. H., Lee, T.-H., Won, C., Lee, C.-H., Moon, J., & Lee, C.-G. (2018). Investigation of the Localized Corrosion and Passive Behavior of Type 304 Stainless Steels with 0.2–1.8 wt % B. *Materials*, *11*(11), 2097. https://doi.org/10.3390/ma11112097

Haizhou, W. (2020). *Geosynthetic material tensile strength detection device for hydraulic engineering detection.* CN212254881 (U), 2020-12-29, Tianjin Xinan Eng Testing Co Ltd.

Hamidah, I., Wati, R., & Hamdani, R. A. (2018). Analysis of AISI 304 Tensile Strength as an Anchor Chain of Mooring System. *IOP Conference Series: Materials Science and Engineering*, *367*, 012058. https://doi.org/10.1088/1757-899X/367/1/012058

ISO 4136:2012 Destructive tests on welds in metallic materials—Transverse tensile test. (2012). ISO.

ISO 6892-1: Metallic materials – Tensile testing – Part 1: Method of test at room temperature. (2010). ISO.

Janeczek, A., Tomków, J., & Fydrych, D. (2021). The Influence of Tool Shape and Process Parameters on the Mechanical Properties of AW-3004 Aluminium Alloy Friction Stir Welded Joints. *Materials*, *14*(12), 3244. https://doi.org/10.3390/ma14123244

Jonak, J., Karpiński, R., & Wójcik, A. (2021). Influence of the Undercut Anchor Head Angle on the Propagation of the Failure Zone of the Rock Medium—Part II. *Materials, 14*(14), 3880. https://doi.org/10.3390/ma14143880

Kawecki, B., & Podgórski, J. (2017). Numerical results quality in dependence on abaqus plane stress elements type in big displacements compression test. *Applied Computer Science*, *13*(4), 56–64. https://doi.org/10.23743/acs-2017-29

Kilicaslan, M. F., Elburni, S. I., & Akgul, B. (2021). The Effects of Nb Addition on the Microstructure and Mechanical Properties of Melt Spun Al-7075 Alloy. *Advances in Materials Science*, *21*(2), 16–25. https://doi.org/10.2478/adms-2021-0008

Kłonica, M. (2018). Analysis of the effect of selected factors on the strength of adhesive joints. *IOP Conference Series: Materials Science and Engineering*, *393*, 012041. https://doi.org/10.1088/1757-899X/393/1/012041

Kowal, M., & Szala, M. (2020). Diagnosis of the microstructural and mechanical properties of over century-old steel railway bridge components. *Engineering Failure Analysis*, *110*, 104447. https://doi.org/10.1016/j.engfailanal.2020.104447

Lubas, M., & Witek, L. (2021). Influence of Hole Chamfer Size on Strength of Blind Riveted Joints. *Advances in Science and Technology. Research Journal*, *15*(2), 49–56. https://doi.org/10.12913/22998624/135632

Lyalin Mikhajlovich, V., Zykov Mikhajlovich, S., & Sidorov Aleksandrovich, R. (2021). *Installation for Dynamic Tensile Testing of Flat Samples of Materials*. RU2744319 (C1). Federalnoe Gosudarstvennoe Byudzhetnoe Obrazovatelnoe Uchrezhdenie Vysshego Obrazovaniya Tulskij Gos.

Łabanowski, J., Jurkowski, M., Fydrych, D., & Rogalski, G. (2017). Durability of welded water supply pipelines made of austenitic stainless steels. *Welding Technology Review*, *89*(8), 35–40. https://doi.org/10.26628/wtr.v89i8.801

Macek, W., Branco, R., Trembacz, J., Costa, J. D., Ferreira, J. A. M., & Capela, C. (2020). Effect of multiaxial bending-torsion loading on fracture surface parameters in high-strength steels processed by conventional and additive manufacturing. *Engineering Failure Analysis*, *118*, 104784. https://doi.org/10.1016/j.engfailanal.2020.104784

Macek, W., Szala, M., Trembacz, J., Branco, R., & Costa, J. (2020). Effect of non-zero mean stress bending-torsion fatigue on fracture surface parameters of 34CrNiMo6 steel notched bars. *Production Engineering Archives*, *26*(4), 167-173. https://doi.org/10.30657/pea.2020.26.30

Machrowska, A., Karpiński, R., Jonak, J., Szabelski, J., & Krakowski, P. (2020). Numerical prediction of the component-ratio-dependent compressive strength of bone cement. *Applied Computer Science*, *16*(3), 88–101. https://doi.org/10.23743/acs-2020-24

Mahmood, M. A., Popescu, A. C., Oane, M., Chioibasu, D., Popescu-Pelin, G., Ristoscu, C., & Mihailescu, I. N. (2021). Grain refinement and mechanical properties for AISI304 stainless steel single-tracks by laser melting deposition: Mathematical modelling versus experimental results. *Results in Physics*, *22*, 103880. https://doi.org/10.1016/j.rinp.2021.103880

Nedeloni, M. D., Birtărescu, E., Nedeloni, L., Ene, T., Băra, A., & Clavac, B. (2018). Cavitation Erosion and Dry Sliding Wear Research on X5CrNi18-10 Austenitic Stainless Steel. *IOP Conference Series: Materials Science and Engineering*, *416*, 012028. https://doi.org/10.1088/1757-899X/416/1/012028

Nowacki, J., Sajek, A., & Matkowski, P. (2016). The influence of welding heat input on the microstructure of joints of S1100QL steel in one-pass welding. *Archives of Civil and Mechanical Engineering*, *16*(4), 777–783. https://doi.org/10.1016/j.acme.2016.05.001

Pańcikiewicz, K., Świerczyńska, A., Hućko, P., & Tumidajewicz, M. (2020). Laser Dissimilar Welding of AISI 430F and AISI 304 Stainless Steels. *Materials*, *13*(20), 4540. https://doi.org/10.3390/ma13204540

Pezowicz, C., Szotek, S., Kobielarz, M., & Wudarczyk, S. (2016). *Device for biaxial stretching of biological samples*. PL412122 (A1), 2016-11-07, Wojewódzki Szpital Specjalistyczny We Wrocławiu.

Rout, M. (2020). Texture-tensile properties correlation of 304 austenitic stainless steel rolled with the change in rolling direction. *Materials Research Express*, *7*(1), 016563. https://doi.org/10.1088/2053-1591/ab677c

Różyło, P., Wysmulski, P., & Falkowicz, K. (2017). Fem and Experimental Analysis of Thin-Walled Composite Elements Under Compression. *International Journal of Applied Mechanics and Engineering*, *22*(2), 393–402. https://doi.org/10.1515/ijame-2017-0023

Rudawska, A., Zaleski, K., Miturska, I., & Skoczylas, A. (2019). Effect of the Application of Different Surface Treatment Methods on the Strength of Titanium Alloy Sheet Adhesive Lap Joints. *Materials*, *12*(24), 4173. https://doi.org/10.3390/ma12244173

Sarre, B., Flouriot, S., Geandier, G., Panicaud, B., & de Rancourt, V. (2016). Mechanical behavior and fracture mechanisms of titanium alloy welded joints made by pulsed laser beam welding. *Procedia Structural Integrity*, *2*, 3569–3576. https://doi.org/10.1016/j.prostr.2016.06.445

Skowrońska, B., Chmielewski, T., Kulczyk, M., Skiba, J., & Przybysz, S. (2021). Microstructural Investigation of a Friction-Welded 316L Stainless Steel with Ultrafine-Grained Structure Obtained by Hydrostatic Extrusion. *Materials*, *14*(6), 1537. https://doi.org/10.3390/ma14061537

Szala, M., Chocyk, D., Skic, A., Kamiński, M., Macek, W., & Turek, M. (2021). Effect of Nitrogen Ion Implantation on the Cavitation Erosion Resistance and Cobalt-Based Solid Solution Phase Transformations of HIPed Stellite 6. *Materials*, *14*(9), 2324. https://doi.org/10.3390/ma14092324

Szala, M., & Łukasik, D. (2018). Pitting Corrosion of the Resistance Welding Joints of Stainless Steel Ventilation Grille Operated in Swimming Pool Environment. *International Journal of Corrosion*, *2018*, 9408670. https://doi.org/10.1155/2018/9408670

Szala, M., Sawa, M., & Walczak, M. (2021). *Device for specimens uniaxially tensile strength tesitng (Urządzenie do statycznego, jednoosiowego rozciągania próbek)* (Poland Patent Nr P.437489).

Szala, M., Szafran, M., Macek, W., Marchenko, S., & Hejwowski, T. (2019). Abrasion Resistance of S235, S355, C45, AISI 304 and Hardox 500 Steels with Usage of Garnet, Corundum and Carborundum Abrasives. *Advances in Science and Technology. Research Journal*, *13*(4), 151–161. https://doi.org/10.12913/22998624/113244

Szala, M., Winiarski, G., Wójcik, Ł., & Bulzak, T. (2020). Effect of Annealing Time and Temperature Parameters on the Microstructure, Hardness, and Strain-Hardening Coefficients of 42CrMo4 Steel. *Materials*, *13*(9), 2022. https://doi.org/10.3390/ma13092022

Szklarek, K., & Gajewski, J. (2020). Optimisation of the Thin-Walled Composite Structures in Terms of Critical Buckling Force. *Materials*, *13*(17), 3881. https://doi.org/10.3390/ma13173881

Świć, A., Gola, A., Sobaszek, Ł., & Orynycz, O. (2020). Control of Machining of Axisymmetric Low-Rigidity Parts. *Materials*, *13*(21), 5053. https://doi.org/10.3390/ma13215053

Zagórski, I., Kulisz, M., Kłonica, M., & Matuszak, J. (2019). Trochoidal Milling and Neural Networks Simulation of Magnesium Alloys. *Materials*, *12*(13), 2070. https://doi.org/10.3390/ma12132070

Zheng, C., Liu, C., Ren, M., Jiang, H., & Li, L. (2018). Microstructure and mechanical behavior of an AISI 304 austenitic stainless steel prepared by cold- or cryogenic-rolling and annealing. *Materials Science and Engineering: A*, *724*, 260–268. https://doi.org/10.1016/j.msea.2018.03.105

Żebrowski, R., Walczak, M., Korga, A., Iwan, M., & Szala, M. (2019). Effect of Shot Peening on the Mechanical Properties and Cytotoxicity Behaviour of Titanium Implants Produced by 3D Printing Technology. *Journal of Healthcare Engineering*, *2019*, 8169538. https://doi.org/10.1155/2019/8169538