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Transformative Use of Additive Technology in Design and Manufacture of Hydraulic Actuator for Fly-by-Wire System

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Abstract: In this paper, the results of research on additively manufactured aerospace parts made of maraging steel are presented. This state-of-the-art technology seems to have the highest potential for practical use in the field of ultra-light and high-performance aerospace hydraulic parts. The strength properties of representative specimens made with steel 1.2709 were investigated. The researchers conducted static tensile testing, fatigue tensile testing, and pressure impulse testing. A Goodman diagram was plotted to visualize the impact of the building orientation vs. load character on the fatigue strength of the additive manufacturing (AM) specimens. Based on the research carried out on the strength of the AM samples, an aircraft flight control actuator was designed to achieve the highest level of safety integrity along with the greatest simplicity and lowest weight relative to hydraulic actuators manufactured using classical methods. The entire design process was integrated with the manufacturing process to achieve this target.

Keywords: additive manufacturing; selective laser melting; maraging steel; mechanical properties; fatigue; hydraulics; aerospace systems; fly-by-wire; FBW; actuators

1. Introduction

The actuators used in aircraft flight control systems are most often hydraulic elements [1–3], although in "more electric" [4–6] or "all-electric" aircraft [7,8], electromechanical actuators are also successfully used [9,10]. Hybrid servos can also be found in aviation onboard systems [11]. Hydraulic actuators ensure the transmission of very high power in relation to their weight [12], surpassing both electromechanical and pneumatic systems in this respect. The power of hydraulic systems is relatively easy to maintain and control, and properly designed and operated hydraulic systems are extremely reliable and safe [13]. Their structure is strictly defined by standards [14]. The hydraulic controls are automated [15], allowing direct operation, for example, the position of the actuator. The biggest disadvantages of hydraulic systems include the high costs related to the construction of their installation. They also require regular inspection and maintenance, and breakdowns related to the occurrence of leaks in the hydraulic system are particularly troublesome [12]. Designing actuators for control surfaces requires special consideration of the aspects related to their reliability, operational safety, and long-term operation in unfavorable environmental conditions (e.g., large-amplitude changes in ambient temperature, air pressure, and exposure to vibrations and shocks) [13–15]. Hydraulic systems made using classic technologies have long been able to meet these requirements.

In view of current environmental degradation, the rise of fuel prices, and constrained sourcing and gathering of renewable energy, the aerospace industry needs to constantly conduct research on new materials and technologies. Reducing the total weight of an aircraft constitutes one of the most important tasks for contemporary aviation. Decreasing the weight of medium- and long-haul aircraft by 1 kg enables saving up to 150 liters of fuel per year [16]. Therefore, since fire-resistant oils based on phosphoric esters (e.g.,



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Skydrol or HyJet [17]) are more lightweight than mineral oils by up to 7%, they have been applied in the field of hydraulic systems for several years. Despite research conducted on ways to increase the endurance of the most frequently applied aluminum, titanium, and stainless steel alloys used in the components of aircraft hydraulics, reducing the weight of mechanical components is considerably more difficult. It is estimated that the value of every reduced kilogram of the weight of an aircraft may be anything from USD 100 to USD 2000 [18]. In the context of reducing the weight of the aircraft, and thus reducing fuel consumption, CO_2 emissions, harmful substances, and noise emissions, taking actions related to the design, production, and implementation of lighter actuators realized in additive technology seems to be the right thing to do. This is also confirmed by the attempts being made by major producers in the aviation market [19]. The potential for the application of additive technologies in aircraft looks promising, and machine producers already have devices dedicated to metal printing that may be used to manufacture parts on an industrial scale [20–22].

The Domin company, in cooperation with Rzeszów University of Technology, conducted extensive research on the endurance of maraging steel 1.2709 as far as the process of laser melting is concerned (the actual research of SLM technology in relation to maraging steel 1.2709 is also described in the work of other teams [23,24]). Furthermore, researchers have assessed whether the material in question may be used in aircraft for hydraulic components [25]. Hydraulic actuators have a highly complex internal structure, especially regarding operating conditions. Such a structure is particularly noticeable in a characteristic of the actuator presented in this paper and dedicated to the fly-by-wire (FBW) control system. Due to the lack of direct mechanical connection between the inceptors (steering wheel and mini side-stick) and the actuators of the control surfaces, FBW systems require very high reliability and there must also be multiple (redundant) systems [26–30]. In this study, it was of interest to investigate the mechanical properties of additive manufacturing (AM) samples produced by SLM and the potential of the application of this technology in the design and manufacture of hydraulic components for aerospace. A previous study carried out on the design of the presented actuator demonstrated the performance of maraging steel sleeves produced by SLM with subsequent age hardening [25]. This paper presents the extended results of mechanical tests of SLM samples, including tensile fatigue and pressure fatigue tests (Sections 2 and 3). The Goodman diagram [31,32] developed based on the fatigue test results for the design of elements made of AM maraging steel is also presented at the end of Section 3. Section 4 presents the structure of the actuator and photographs showing selected stages of the implementation of an element in SLM technology. This section also presents a working prototype of an actuator made with AM technology.

2. Mechanical Properties of Maraging Steels

High-strength maraging steels constitute a special class of low-carbon iron-nickel alloys with a martensitic structure hardened by precipitates. The main alloying elements to which this steel owes its strength and ductility are Ni, Co, and Mo [33]. In industry, the most commonly used maraging steels are those with 18% nickel content. This element increases hardenability, enabling martensitic transformation during air-cooling, and increases resistance to fracture. Cobalt reduces the solubility of molybdenum, which greatly increases the ductility of steel and allows the addition of other elements that strengthen the structure of the material, primarily titanium. Table 1 shows the most popular maraging steels.

Grade	Wrought		Cast		AM Powder	
	18Ni1400	18Ni1700	18Ni1900	18Ni2400	17Ni1600	M300/1.2709
Nominal 0.2% Proof Stress (MPa)	1400	1700	1900	2400	1600	1800
Ni	17–19	17–19	18–19	17–18	16-17.5	17–19
Со	8.0-9.0	7.0-8.5	8.0-9.5	12–13	9.5-11.0	8.5-9.5
Мо	3.0-3.5	4.6-5.1	4.6-5.2	3.5-4.0	4.4-4.8	4.5-5.2
Ti	0.15-0.25	0.3-0.5	0.5-0.8	1.6-2.0	0.15-0.45	0.6-0.8
Al	0.05-0.15	0.05-0.15	0.05-0.15	0.1-0.2	0.02-0.1	0.05-0.15
Si max.	0.12	0.12	0.12	0.1	0.1	0.1
Mn max.	012	0.12	0.12	0.1	0.1	0.1
C max.	0.03	0.03	0.03	0.01	0.03	0.03
Fe	Balance	Balance	Balance	Balance	Balance	Balance

Table 1. Chemical composition of the most popular maraging steels [33–35].

The heat treatment of maraging steel requires annealing at a temperature of 800–900 $^{\circ}$ C and air-cooling, allowing the attainment of a hardness of 55 HRC and a maximum with-standable stress R_m from 1700 MPa to 2400 MPa [34]. Furthermore, the strongest maraging steels achieve their endurance limit at approximately 900 MPa for R = 0.1, where R is the minimum peak stress divided by the maximum peak stress [34].

3. Verification of the Strength of Age-Hardened Maraging Steel Samples Produced with SLM Technology

3.1. Tensile Testing

The static tensile test was performed using an Instron 3382 machine. The tests were carried out on 10 samples of circular cross section with a nominal initial diameter of $d_0 = 6$ mm, a nominal length of the measuring section of $l_0 = 25$ mm, and an as-built surface finish of Ra 5–12 µm. Each sample had a unique name, for example, P1/128/01, etched on by a laser machine. The samples were printed by an SLM 250 machine with a 50 µm layer thickness setup. The tests were carried out at room temperature according to the standard PN-EN ISO 6892-1: 2016-09. The test results are presented in Table 2. When analyzing the obtained results, it was observed that the elongation under fracture (parameter A) varied from 1.2% to 6.9%, while diameter reduction (parameter Z) varied between 5% and 21%. The parameter R_{0.2} is the 0.2% offset yield strength. Additionally, for some samples, the curves of the change in internal stress in the sample as a function of strain were recorded (Figure 1).

Sample No.	R _{0.2} (MPa)	R_m (MPa)	A (%)	Z (%)
P1/128/01	1317	1432	2.9	18
P1/128/02	1359	1450	5.1	21
P1/128/03	1445	1530	4.4	21
P1/128/04	1309	1397	1.2	5
P1/128/05	1530	1603	2.8	13
P1/128/06	1338	1417	6.8	10
P1/128/07	1268	1336	2.8	5
P1/128/08	1259	1347	6.0	6
P1/128/09	1204	1287	4.8	8
P1/128/10	1442	1514	6.9	13

 Table 2. Tensile testing results.

1600



Figure 1. Tensile stress-strain curves.

Comparing the obtained results with the technical specifications of maraging steels produced in a conventional manner, the tensile strength of the printed samples in this case was comparable to that of 18Ni1400 and approximately 16% lower than that of 18Ni1700.

3.2. Tensile Fatigue Testing

Fatigue tests were carried out using an Instron 8801 machine (Figure 2) on samples of circular cross section with an as-built surface finish and a 50 μ m layer setup, the shapes and dimensions of which were in accordance with the ASTM E466-15 standard. The build orientation of the specimens was 0 degrees with respect to the sample's longitudinal axis. The tests were carried out at room temperature with a cyclically changing load at a frequency f = 3 Hz. The stresses arising in the sample were defined as one-sided tension with a cycle asymmetry R = 0.05. The results of measured minimum stress σ_{min} and maximum stress σ_{max} in the sample for fatigue life (N_f) are presented in Table 3. These parameters were used to determine the S–N curve (Figure 3).



Figure 2. The laboratory test rig Instron 8801.

Sample No.	σ _{max} (MPa)	σ _{min} (MPa)	N_f (Cycles)
R1/128/01	1200	60	216
R1/128/02	1000	50	1237
R1/128/03	800	40	3504
R1/128/04	600	30	22,077
R1/128/05	450	22.5	31,324
R1/128/06	300	15	47,489
R1/128/07	250	12.5	111,361
R1/128/08	210	10.5	300,000 *
R1/128/09	200	10	300,000 *

Table 3. Tensile fatigue test results.

* - unbroken samples



Figure 3. The S–N curve for additively manufactured maraging steel, R = 0.05.

Comparison of the obtained results with the literature data revealed that the samples made with the additive technologies were damaged at a much lower load. Based on the test results at 300,000 cycles, it can be concluded that the AM samples were approximately 16% less resistant to fatigue compared with the weakest maraging steels.

3.3. Pressure Fatigue Testing

The pressure fatigue tests were carried out on a test rig (Figure 4). The internal diameters of the samples (Figure 5) were 22, 27, and 33 mm and the wall thicknesses were 0.4, 0.5, and 0.6 mm. The build orientation of the sleeves was 0 degrees with respect to the sample's rotational axis. The samples were sandblasted and machined to achieve good sealing surfaces, leaving the internal and external cross sections in the middle with an as-built surface finish and a 50 μ m layer setup. The samples were placed in a steel block in the test chamber of the rig. On the basis of the measurement of the hydraulic oil pressure, the cylindrical stresses were determined using the following relationship:

$$\sigma_{\theta} = \frac{Pd}{2t} \tag{1}$$



where σ_{θ} is cylindrical stress, *P* is pressure, *d* is internal diameter, and *t* is wall thickness.

Figure 4. The pressure fatigue test rig.



Figure 5. Pressure fatigue samples.

The stresses arising in the sample were controlled by the maximum values of the pressure pulses (Figure 6) at a frequency f = 5 Hz. The control system counted the pressure pulses until the sample was broken. The results of the pressure fatigue tests are presented in Table 4. Based on Table 4, the S–N curve was created (Figure 7). The pressure fatigue endurance limit was more than 50% higher in comparison with tensile tests of the AM samples.



Figure 6. Pressure impulse waveform.

Sample No.	<i>t</i> (mm)	P (psi)	σ_{max} (MPa)	N_f (Cycles)
X0937	0.4	2900	592	15,052
X0938	0.4	3600	735	20,452
X0939	0.4	2200	449	52,125
X0940	0.4	4895	1000	4474
X0941	0.4	1375	281	1,000,000 *
X0942	0.4	1700	347	1,000,000 *
X0949	0.5	1375	276	1,000,000 *
X0950	0.5	1600	321	1,000,000 *
X0951	0.5	1850	371	301,249
X0952	0.5	2600	521	88,639
X0953	0.5	2250	451	99 <i>,</i> 572
X0954	0.5	3000	601	40,106
X0961	0.6	1375	293	1,000,000 *
X0962	0.6	1600	341	1,000,000 *
X0963	0.6	1850	394	278,403
X0964	0.6	2600	554	119,877
X0965	0.6	4050	863	2920
X0966	0.6	2816	600	89,037

 Table 4. Pressure fatigue test results.

*—unbroken samples



Figure 7. The S–N curve for AM maraging steel for pressure fatigue load, R = 0.

3.4. Goodman Diagram for Designing AM Maraging Steel Components for Fatigue

The data from the tensile and fatigue testing were used to plot the Goodman diagram as a reference for engineers who are involved in additive manufacturing design processes. The yield strength, ultimate strength, and endurance limit points were calculated in Table 5 and plotted in Figure 8.

Table 5. Calculated material data.

Mechanical Data	Average Stress Values	Maximal Error
Yield strength	1347 MPa	13%
Ultimate strength	1431 MPa	12%
Tensile fatigue strength, mean, $R = 0.05$	97 MPa	8%
Pressure fatigue strength, mean, $R = 0$	155 MPa	11%



Figure 8. Goodman diagram obtained from fatigue and static testing of the maraging steel specimens produced by SLM.

The Goodman diagram shows the influence of build orientation on the fatigue properties. AM parts that were loaded in the same direction as the build orientation indicated lower fatigue strength. This effect is widely known in AM technology, and has been extensively analyzed in the literature [36–39]; however, the diagram presented in Figure 8 is the quantitative result obtained by the authors of the work in relation to the selected material and technology in which the presented actuators are made.

4. The Use of SLM Technology in the Production of Aviation Hydraulic Parts

4.1. The Process of Manufacturing and Integrating the Hydraulic Actuator

Based on the research carried out on the strength of the AM samples, the aircraft flight control actuator was designed to achieve the highest level of safety integrity along with the greatest simplicity and lowest weight. The architecture aims to simplify the methods of failure detection, which need to be included within the flight control computer [31–43]. The general schematic of the flight control actuator (FCA) is presented in Figure 9. The servo actuator system is a dual tandem configuration with a hydro-mechanical anti-jam mechanism. It has two direct-drive servo valves with mechanical feedback linkage from the main ram to the secondary outer sleeve of the servo valve.



Figure 9. General schematic drawing of the FCA; own drawing based on patent [40] and Domin company materials [41].

The center manifold is a key part of the actuator. It contains a rotary torque motor, two rotary spools, two sleeves, and position sensors coupled on one shaft. The electronic system is a fully quadruplex architecture and is fail operational even in the event of three failures. It includes a redundant three-phase channel motor with independent drives for each control lane. Each of the stator sectors is mechanically separated and capable of driving the load of the rotor in the event of failure. All hydraulic elements inside the valve are pressure- and flow-balanced in order to achieve low friction and hysteresis. The servo valve cross section schema is presented in Figure 10.

A dual hydraulic arrangement with independent valves allows one failure—either mechanical or hydraulic—without performance loss. The actuator receives four electrical command signals and two hydraulic supplies. The actuator can produce ram displacement in response to electrical command signals and continue operation after the failure of any input or internal part.

FCAs are complex items. The use of AM technology has significantly influenced the design and manufacture of many complex components included within the assembly of the actuator to meet the rigorous safety-critical requirements. Selected elements of FCAs manufactured by AM technology and the full assembly of the complete actuator are presented in Figures 11–14. The presented FCA is lighter and has fewer parts [42]. It is approximately half the weight of the equivalent mechanical servo and less than half the weight of any FBW alternative.



Figure 10. General schematic of the servo; own drawing based on patent [40] and Domin company materials [41].



Figure 11. Manufacturing of actuator bodies with AM technology.



Figure 12. Actuator components made with AM technology ready for integration: primary control sleeves.



Figure 13. Actuator components made with AM technology ready for integration: primary control spools.



Figure 14. Assembled fly-by-wire actuator manufactured with AM technology.

4.2. Results of the Preliminary Dynamic Tests

The complete mechanical prototype of the actuator was prepared for initial dynamic tests (Figure 15). These tests were performed with an operating pressure limited to 100 bar. A dedicated electro-mechanism was used for the positioning of the piston rod, together with a proprietary control and measuring system. The obtained actuator responses to the

step input and the sawtooth input are shown in Figures 16 and 17. The analysis of the step characteristic shows that with the limited working pressure, the actuator movement speed was approximately 75 mm/s (the full range of movement is 140 mm). For a sawtooth excitation, the delay was tens of milliseconds and the error in the actuator dynamic response was not greater than 7.5 mm (Figure 17). Detailed and complete tests of the actuators will be possible only after the completion of the work related to the dedicated control system. The development of an actuator control system is a complex and interdisciplinary issue. The effective dynamics of the actuator in its final form will result from both its mechanical properties and the properties of the controller itself.



Figure 15. The actuator prototype prepared for preliminary functional tests.



Figure 16. The actuator response to the step input.



Figure 17. The actuator response to a triangle-shaped input.

5. Conclusions

This study investigated the use of SLM technology in the production of aviation hydraulic parts. The results of the static tensile tests indicated that parts produced by SLM achieved similar tensile strength to the maraging steel 18Ni1400 produced in a conventional manner. Comparison of the tensile fatigue results with the literature data revealed that the samples made with the additive technologies were broken at a lower load. Based on the test results at 300,000 cycles, it can be concluded that the AM samples are approximately 16% less resistant to fatigue compared with the weakest maraging steels.

A Goodman diagram was plotted to visualize the impact of the building orientation vs. the load character on the fatigue strength of the AM specimens. Directions of load, stress, and building orientation in the samples tested for tensile fatigue were 0 degrees with respect to the specimen's longitudinal axis, and these specimens achieved a lower number of cycles to failure in comparison with pressure fatigue specimens. In contrast to the tensile testing, the pressure acting on the internal wall of the sleeves generated circumferential hoop stresses at 90 degrees to the specimen's build direction. The analysis of the fatigue tests shows that the fatigue limit cannot be strictly determined and is highly dependent on the load vs. the built direction. These findings are consistent with other research and relevant literature [24,44].

The application of additive technologies in aviation may completely redefine the design and manufacture of advanced hydraulic aircraft control systems; however, the design process should be well integrated with the manufacturing process. The build orientation and character of load, as seen in the Goodman diagram in Figure 10, can be used as a tool for designing parts for fatigues. The authors prepared this diagram based on experimental data, and it is valid for steel 1.2709. SLM technology allows the manufacture of components with functional and complex internal structures, such as channels and flow-through bores, with weights decreased by up to 50%.

All dual servo valve ports were printed and directly connected with the external hydraulic ports on the actuator housing by complex internal galleries, allowing full redundancy of the system and complete mechanical separation of the flow paths [42]. Changing the cross-sectional area of the internal ports enabled the packing of two hydraulic servo valves and anti-jam control sleeves into a center gland housing with an unprecedented level of integration. This approach to designing hydraulic parts could revolutionize fluid

power systems and significantly increase their potential in the aerospace industry. The use of 3D printing allows for significant reductions in the number of parts required for larger assemblies. The manufacture of parts by means of the technology in question decreases the usage of the target material, and thus the waste material (the turnings) is reduced to a minimum.

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