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UNCONVENTIONAL METHODS OF MANUFACTURING THIN WIRES FOR APPLICATION AS INPUT MATERIAL IN ADDITIVE MANUFACTURING. PART 2: DRAWING OF Fe-BASED ALLOY WIRES

NIEKONWENCJONALNE METODY WYTWARZANIA CIENKICH DRUTÓW STALOWYCH DO ZASTOSOWANIA JAKO MATERIAŁ WSADOWY W TECHNOLOGIACH PRZYROSTOWYCH. CZĘŚĆ 2: CIĄGNIENIE DRUTÓW ZE STOPÓW NA BAZIE Fe

The article presents the technology of drawing thin wires made from selected iron-based alloys for use in additive manufacturing using WAAM method. The final technology of wire production was developed with the use of a drawing bench, depending on the deformed material. Steel wires with a diameter of 1 mm and mechanical properties adapted to the 3D printer were produced.

Keywords: *additive manufacturing, wire, drawing, draft*

W artykule przedstawiono technologię wykonania cienkich drutów z wybranych stopów na bazie Fe do zastosowania w technologiach przyrostowych metodą WAAM. Finalną technologię wykonania drutu opracowano z zastosowaniem ciągarki ławowej w zależności od odkształcanego materiału. Wykonano druty stalowe o średnicy 1 mm i właściwościach mechanicznych dostosowanych do drukarki 3D.

Słowa kluczowe: *technologia przyrostowa, drut, ciągnienie, gniot*

1. INTRODUCTION

Chemical compositions of Fe-based alloys for the production of powder or wire, i.e. semi-finished products for additive technologies, were developed as part of project No. 410049 (Techmatstrateg 2) "Modern iron-based and copper-based alloys intended for the production of products with a designed structure and properties using additive technologies". Part 1 of the article presents the technological path of manufacturing semi-finished products for wires for additive technologies from the moment of steel smelting to the production of bars with a diameter of ϕ5 mm [1].

The aim of the article is to present the technology of making input material for 3D printers in the form of a wire with a diameter of ϕ1 mm from three selected Fe-based alloys developed as part of the project, against the background of the requirements for wires to be used in WAAM (wire arc additive manufacturing) devices, i.e. a process based on applying layers of material using protective gas arc welding with the use of an electrode wire.

2. DEVELOPMENT OF PRELIMINARY TECHNOLOGY FOR DRAWING WIRES INTENDED FOR ADDITIVE TECHNOLOGIES

2.1. Assumptions for the production technology for wires for additive technologies

A manufacturer of the device for 3D printing using the WAAM method has defined the following critical

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parameters of wires for use in additive technologies [2]:
– wire's diameter: 1.00 mm or 1.2 mm
– tensile strength of the wire: R_m = 950–1250 MPa
– percentage elongation of the wire: A_{100} = 4–6 %.

The wire should be wound on an SD 300 reel with a maximum wire weight of 15 kg.

2.2. STRENGTH PROPERTIES OF WIRES MADE OF SELECTED STEELS FOR USE IN ADDITIVE MANUFACTURING TECHNOLOGIES

As a result of previous studies, it was established that the wires for additive technologies will be made of 25H2N4MA steel, MS350 maraging steel and 10MFTi steel [1]. Table 1 summarises the basic mechanical properties of these steels obtained with the use of ϕ10M16 mm strength samples (average of two measurements), and Fig. 1 shows tensile diagrams of bars with a diameter of ϕ3 mm made of these steels. For additive manufacturing, three steels with extremely different mechanical properties and their different hardening tendencies were selected: from maraging steels with very high strength and low hardening increments to 10MFTi steels with twice the strength and twice the hardening tendency.

2.3. TECHNOLOGICAL WIRE-DRAWING TESTS

The input for the production of wires were rods with a diameter of approx. ϕ5.2 mm and a length of approx. 1200 mm, made using hydrostatic extrusion and rotary forging in a softened state. As the bars had to be welded together before drawing, preliminary welding tests were carried out, which confirmed that all three steels are fully weldable and the proposed technology of making a wire with a diameter of ϕ1 mm can be implemented.

Pre-drawing was performed on the LPS line at Łukasiewicz – IMŻ with the use of a drawing bench with a maximum thrust of 10 T with data recording. Draw dies with a cone angle of 2α = 12° were used. HLP46 oil was used as the lubricant.

2.3.1. 25H2N4MA steel

Tests of drawing 25H2N4MA steel bars were carried out according to several deformation patterns, using partial draft values from 10 % to 18 %, typical for alloy steels and a different number of draws (Table 2) [3–7]. After selected drawing stages, wire samples

Table 1. Mechanical properties of steels intended for wires for additive technologies
Tabela 1. Właściwości mechaniczne stali na druty do technologii przyrostowych

Sample identification	Yield strength		Tensile strength	R_e/R_m	Elongation and narrowing		
	$R_{p0.2}$ [MPa]	R_{eH} [MPa]	R_m [MPa]		A_5 [%]	A_{gt} [%]	Z [%]
25H2N4MA	724	–	958	0.76	17.1	6.85	63
MS350	779.5	–	1080	0.72	13.6	2.7	66
10MFTi	466.5	470	575	0.82	23.4	9.1	75

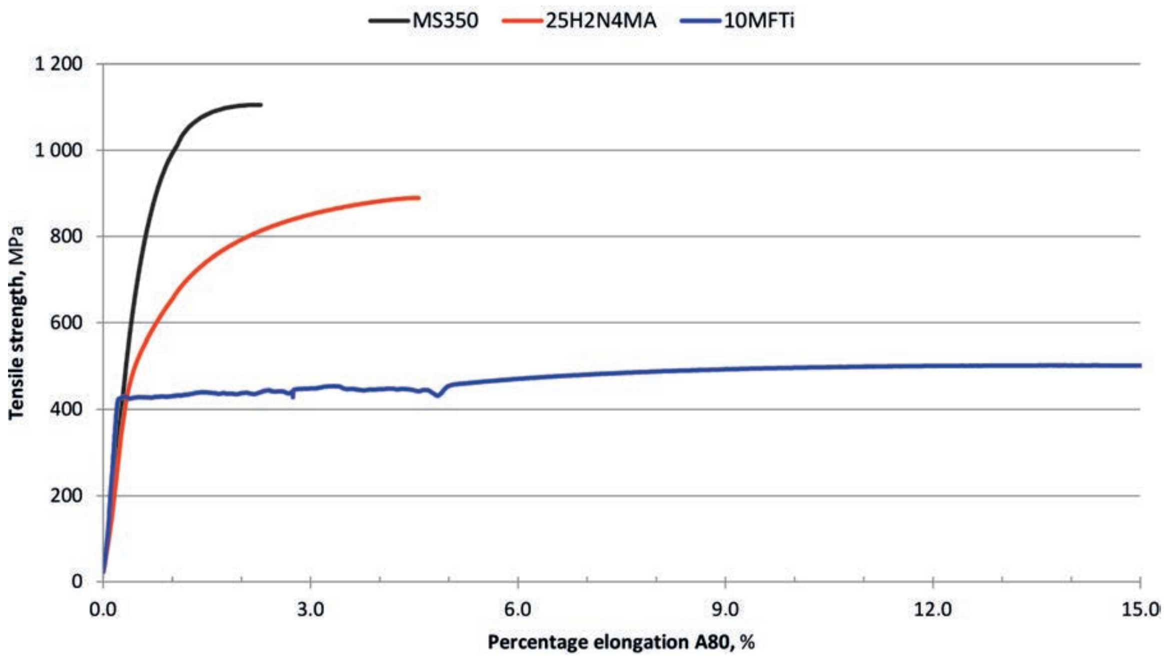

Fig. 1. Graphs for drawing wires made of steels intended for additive technologies
Rys. 1. Wykresy rozciągania prętów ze stali przeznaczonych do technologii przyrostowych

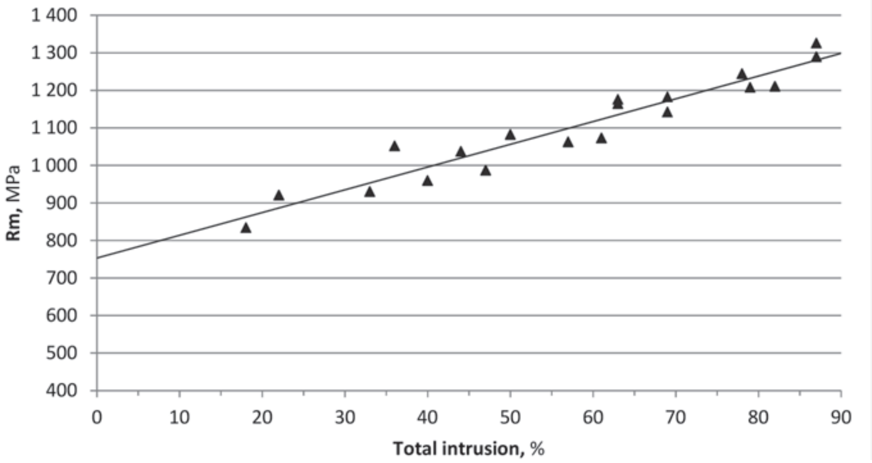

Fig. 2. Tensile strength of 25H2N4MA steel bars depending on total draft

Rys. 2. Wytrzymałość na rozciąganie prętów ze stali 25H2N4MA w zależnosci od gniotu sumarycznego

Table 2. Technological parameters of drawing bars made of 25H2N4MA steel

Tabela 2. Parametry technologiczne ciągnienia prętów ze stali 25H2N4MA

Test No.	Number of draws	Average draft	Total draft
	–	%	%
1	15	10.8	82
2	14	10.5	79
3	13	14.1	86
4	10	18.2	87

Table 3. Technological parameters of drawing bars made of MS350 maraging steel

Tabela 3. Parametry technologiczne ciągnienia prętów ze stal maraging MS350

Test No.	Number of draws	Average draft	Total draft
	–	%	%
1	14	11.3	81
2	11	9.5	67
3	9	14.5	76
4	7	12.8	62

were taken for testing mechanical properties and hardness measurement. Fig. 2 shows the results of tensile strength of 25H2N4MA steel bars in relation to the total draft that was applied when drawing bars. As seen above, the tensile strength of the 25H2N4MA steel wire changes with the strain increase from the initial value of approx. 750 MPa in the softened state to approx. 1300 MPa after drawing with a total draft of approx. 87 %.

2.3.2. MS350 maraging steel

In the case of MS350 maraging steel, lower values of partial and total drafts were used than for 25H2N-4MA steel due to the greater strengthening of the maraging steel (Table 3). Fig. 3 shows the results of tensile strength of maraging steel bars in relation to the total draft that was applied when drawing bars. Maraging steel has a much higher tensile strength than 25H2N4MA steel.

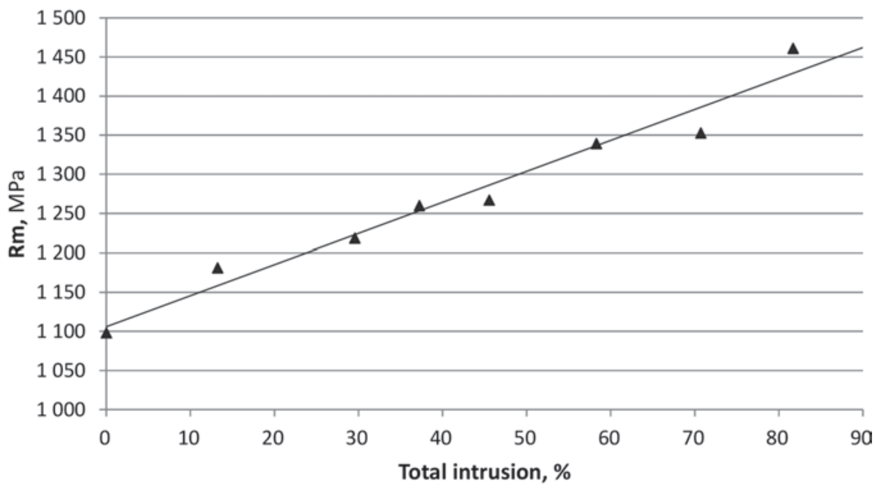

Fig. 3. Tensile strength of maraging steel bars depending on total draft

Rys. 3. Wytrzymałość na rozciąganie prętów ze stali maraging w zależnosci od gniotu sumarycznego

2.3.3. 10MFTi steel

10MFTi steel bars were drawn with partial drafts in the range from 10 % to 18 %. The maximum total draft was approx. 90 % (Table 4). Fig. 4 shows the increment of total draft in individual draws during drawing of 10MFTi steel, and Fig. 5 shows the results of tensile strength in relation to the total draft that was applied when drawing bars. As seen above, 10MFTi steel has much lower tensile strength than 25H2N-4MA steel, maraging steel and 25H2N4MA steel.

Table 4. Technological parameters of drawing bars made of 10MFTi steel

Tabela 4. Parametry technologiczne ciągnienia prętów ze stali 10MFTi

Test No.	Number of draws	Average draft	Total draft
	-	%	%
1	16	10.7	84
2	14	12.8	85
3	14	14.9	90
4	10	18.0	86

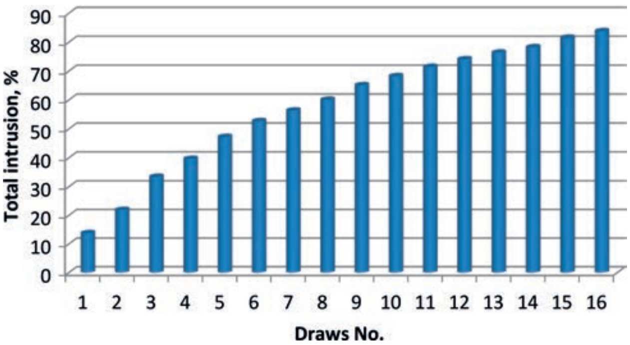

Fig. 4. Increase of total draft in individual draws during drawing 10MFTi steel

Rys. 4. Wzrost gniotu sumarycznego w poszczególnych ciągach w trakcie ciągnienia stali 10MFTi

2.4. PROPOSED WIRE PRODUCTION TECHNOLOGY FOR 3D PRINTING

Based on the results of the performed bar drawing tests and in accordance with the guidelines of the manufacturer of the 3D printer, technologies for making ϕ1.0 mm diameter wire from selected steel grades were proposed.

The proposed technology includes:
– drawing diagram,
– heat treatment parameters,
– mechanical cleaning / etching.

2.4.1. 25H2N4MA steel wire

The proposed technology of producing a wire with a diameter of ϕ1.0 mm includes the following operations: bar welding + 7 draws, heat treatment, 7 draws, heat treatment, 7 draws.

As a result, a wire with a diameter of ϕ1.0 mm, strength of approx. 1050 MPa and elongation A_{100} of approx. 4.0 % should be obtained.

3 draft sequences were proposed:
- Ø5.3 → 5.0 → 4.65 → 4.30 → 3.95 → 3.60 → 3.30 → Ø3.05 mm
- Ø3.05 → 2.80 → 2,60 → 2.40 → 2.20 → 2.00 → 1.85 → Ø1.70 mm
- Ø1.70 → 1.60 → 1.50 → 1.40 → 1.30 → 1.21 → 1.11 → Ø1.00 mm.

After each sequence of draws, the wire should be subjected to softening annealing with the following parameters: heating at 670 °C for 6 hours in a protective atmosphere, cooling with the furnace or in still air. Then, mechanical or chemical cleaning must be used to remove the scale from the wire.

2.4.2. MS350 maraging steel wire

The proposed technology of producing a wire with a diameter of ϕ1.0 mm includes the following operations: bar welding + 16 draws, heat treatment, 14 draws, heat treatment and the following variants:

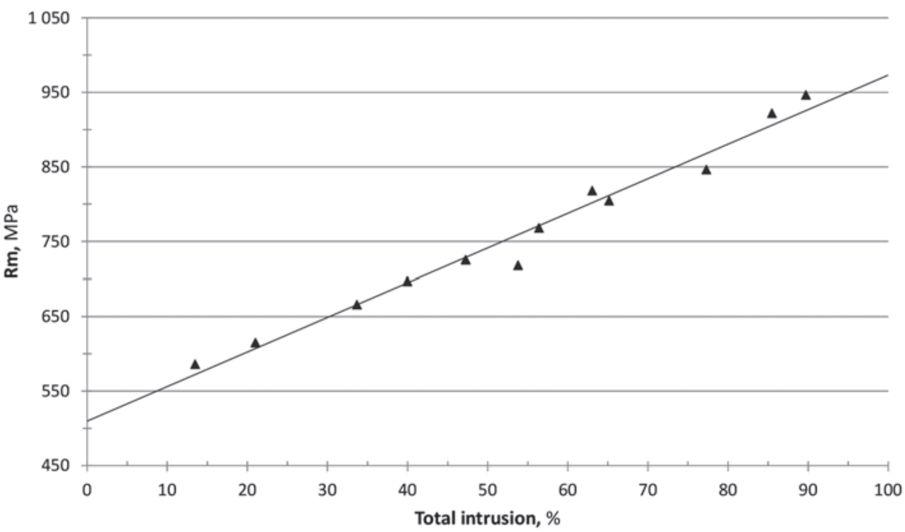

Fig. 5. Tensile strength of 10MFTi steel bars depending on total draft

Rys. 5. Wytrzymałość na rozciąganie prętów ze stali 10MFTi w zależności od gniotu sumarycznego

16 draws, heat treatment or 14 draws, heat treatment, 2 draws.

As a result, a wire with a diameter of ϕ1.0 mm, strength of approx. 1100–1200 MPa and elongation A_{100} of approx. 2.5–4.0 % should be obtained.

3 draft sequences were proposed:
- Ø5.3 → 5.00→ 4.80→ 4.65 → 4.50 → 4.35 → 4.22 → 4.10 → 3.95→ 3.80 → 3.70 → 3.60 → 3.50 → 3.40 → 3.30 → 3.20 → Ø3.10 mm
- Ø2.95 → 2.80 → 2.65 → 2.55 → 2.45 → 2.35 → 2.25 → 2.20 → 2.10 → 2.00 → 1.95 → 1.85 → Ø1.80 mm
- Ø1.70 → 1.60 → 1.53 → 1.45 → 1.40 → 1.35 → 1.30 → 1.25 → 1.21 → 1.17 → 1.13 → 1.11 → 1.07 → 1.05 → 1.02 → Ø1.00 mm.

After each sequence of draws, the wire should be subjected to solution heat treatment with the following parameters: heating at 850 °C for 30 minutes in a protective atmosphere, cooling in water. Then, mechanical or chemical cleaning must be used to remove the scale from the wire.

2.4.3. 10MFTi steel wire

The proposed technology of producing a wire with a diameter of ϕ1.0 mm includes the following operations: bar welding + 8 draws, heat treatment, 18 draws.

As a result, a wire with a diameter of ϕ1.0 mm, strength of approx. 900 MPa and elongation A_{100} of approx. 4.0 % should be obtained.

2 draft sequences were proposed
- Ø5.15 → 4.80 → 4.50 → 4.20 → 3.95 → 3.75 → 3.50 → 3.25 → Ø3.05 mm
- Ø2.80 → 2.65 → 2.50 → 2.35 → 2.20 → 2.10 → 1.95 → 1.82 → 1.70 → 1.60 → 1.50 → 1.40 → 1.30 → 1.23 → 1.17 → 1.10 → 1.05 → Ø1.00 mm.

After the first drawing sequence, the wire should be subjected to softening annealing with the following parameters: heating at 690 °C for 5 hours in a protective atmosphere, cooling with the furnace or in still air. Then, mechanical or chemical cleaning must be used to remove the scale from the wire.

3. DRAWING OF WIRES FOR ADDITIVE TECHNOLOGIES

Drawing of wires was started on the basis of the proposed draft plans. In a few cases, the initial plans were modified to accommodate the drawn material. The wires were drawn at Łukasiewicz – IMN with the use of a single block wire drawing machine and a wet type continuous wire drawing machine.

3.1. 25H2N4MA STEEL WIRES

The following sequences of draws were used while drawing 25H2N4MA steel wires:
- Ø5.3 → 5.0 → 4.80 → 4.65 → 4.50 → 4.30 → 4.10 → 3.95 → 3.80→ 3.60 → 3.45→ 3,30 → 3.15→ Ø3.05 mm (13 draws); due to cracking of welded joints, the values of partial drafts were reduced;
- Ø3.05 →2.85 → 2.70 → 2.55 → 2.40 → 2.25 → 2.10 → 1.95 → 1.83 → Ø1.69 mm (9 draws)
- Ø1.69 → 1.60 → 1.50 → 1.40 → 1.30 → 1.21 → 1.11 → Ø1.00 mm (wet drawing – 7 draws).

Table 5 summarises the results of mechanical properties of the obtained wires with a diameter of ϕ1.0 mm. Figs. 6 and 7 show the wire made of 25H2N-4MA steel, during drawing and after drawing, wound on a reel.

Fig. 6. 25H2N4MA steel wire during drawing with drum-type wire drawing machine

Rys. 6. Drut ze stali 25H2N4MA w czasie ciągnienia na ciągarce bębnowej

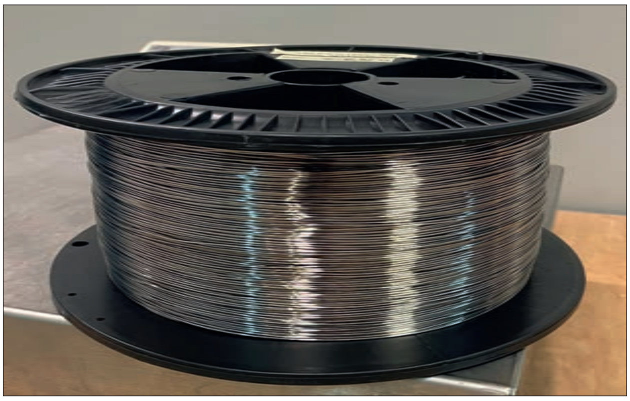

Fig. 7. 25H2N4MA steel wire with a diameter of ϕ1.0 mm

Rys. 7. Drut ze stali 25H2N4MA o średnicy ϕ1,0 mm

Table 5. Mechanical properties of wires with a diameter of ϕ1.0 mm intended for additive technologies

Tabela 5. Właściwości mechaniczne drutów o średnicy ϕ1,0 mm przeznaczonych do technologii przyrostowych

Sample	$R_{p0.2}$ (MPa)	R_m (MPa)	$R_{p0.2}/R_m$ (%)	A_{100} (%)	Z (%)
25H2N4MA	894	990	90.3	2.8	45.3
MS350	1282	1312	97.7	2.9	6.9
10MFTi	780	883	88.3	ruptured beyond base	

3.2. MS350 MARAGING STEEL WIRE

The following sequences of draws were used while drawing MS350 steel wires:

- Ø5.3 → 5.00→ 4.80 → 4.65 → 4.50 → 4.35 → 4.22 → 4.10 → 3.95→ 3.80 → 3.70 → 3.60 → 3.50 → 3.40 → 3.30 → 3.20 → Ø3.10 mm (16 draws)
- Ø2.95 → 2.80 → 2.65 → 2.55 → 2.45 → 2.35 → 2.25 → 2.20 → 2.10 → 2.00 → 1.95 → 1.85 → Ø1.80 mm (12 draws)
- Ø1.70 → 1.60 → 1.53 → 1.45 → 1.42 → 1.35 → 1.30 → 1.25 → 1.21 → 1.17 → 1.13 → 1.11 → 1.07 → 1.05 → 1.02 → Ø1.00 mm (15 draws).

During drawing, the final heat treatment was abandoned for fear of possible surface defects of the wire during etching. Hence the very high strength of the wire with a diameter of ϕ1.0 mm, exceeding the requirements of the 3D printer manufacturer. The initial printing attempts were successful.

3.3. 10MFTI STEEL WIRES

The following sequences of draws were used while drawing 10MFTi steel wires:

- Ø5.15 → 4.80→ 4.50 → 4.20 → 3.95 → 3.75 → 3.50 → 3.25→ Ø3.05 mm (8 draws)
- Ø1.70 → 2.65 → 2.50 → 2.35 → 2.20 → 2.10 → 1.95 → 1.85 → 1.69 → 1.55 → 1.42 → 1.30 → 1.19 → 1.09 → Ø1.00 mm – wet drawing (14 draws).

4. SUMMARY

The article presents the technology of producing wires with a diameter of ϕ1.0 mm for additive technologies using the WAAM method from input material in the form of bars with a diameter of approx. ϕ5.2 mm. The results of preliminary drawing tests with the use of a draw bench aimed at developing the target wire drawing technology are presented and the target wire drawing technology is presented together with the results of mechanical properties.

Wires with a diameter of ϕ1.0 mm were made from three different Fe-based alloys: 25H2N4MA alloy structural steel as a reference material, experimental 10MFTi microalloy steel and maraging steel with the highest yield strength currently available – MS350. Initial attempts to use the obtained wires for 3D printing ended positively.

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