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MECHANICAL ENGINEERING AND MACHINE-BUILDING TECHNOLOGIES

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MODAL ANALYSIS AND FREE VIBRATION TEST PERFORMING AND COMPARING FOR A SIMPLY SUPPORTED BEAM WITH A CRACK

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Abstract: Modal analysis is a linear procedure that calculates natural frequencies through stiffness and mass matrices. But, if there are defects in structures, processes become non-linear. For an example, if a beam has a crack, the stiffness is not constant across the section. This is expected to lead to non-constant moment of inertia over the time when bending vibrations occurs. It is reasonable that an impact may arise to turn the problem into strongly nonlinear. In this paper, the natural frequencies and corresponding modal shapes is firstly obtained for a non-cracked simply supported beam through analytical relations. After that, this is realized for a non-cracked and for a cracked FEM model **by two ways**: a modal analysis based on the stiffness and mass matrices – neglecting the stiffness nonlinearity and the contact interactions; **and a numerical free vibration test – accounting the stiffness nonlinearity and the contact interactions**. The numerical free vibration test uses the Fourier transform to extract the vibration harmonics. Finally, the results are compared and conclusion are claimed.

Keywords: Modal Analysis, Natural Frequencies, Natural Shapes, Beam, Crack, Finite Element Method, Stiffness Nonlinearity, Contact Interactions, Impact, Impact Test, Fourier Transform, Harmonic Analysis, Timediagrams, Spectrograms, Vibration Acceleration, Vibration Velocity, Vibration Displacement.

1. INTRODUCTION

The **modal analysis** of beams provides insights into their **natural frequencies** and **mode shapes**, which are essential for understanding their dynamic response and assessing their health. In (Stoyanov, S., 2017) is presented an investigation of the natural and resonant frequencies of a **cantilever beam**. In (Stoyanov, S., 2018), theoretical and experimental researches of the resonant frequencies of a **plane frame** is performed. The results from the experimental setup created are compared to the theoretically obtained results and it is found that the difference is under 6%.

Most of the members of engineering structures operate under loading conditions, which may cause damages or cracks in overstressed zones (Quila, M., Sarkar, S., 2024). Therefore, the study of cracked beams is a significant area of research in structural engineering and material science. Cracks can severely affect the structural integrity and dynamic behavior of beams, which are critical components in various engineering applications, including bridges, buildings, and machinery. The presence of cracks causes changes in the physical properties and dynamic response characteristics of beams (Jagdale, P., Chakrabarti, M., 2013).

The presence of cracks in beams can lead to catastrophic failures if not detected and addressed in time. Traditional methods for inspecting and maintaining structural integrity often fall short in identifying internal defects such as cracks. Therefore, there is a need for advanced techniques that can accurately predict the effects of cracks on the modal parameters of beams. Theoretical modal analysis not only aids in understanding the fundamental dynamics of cracked beams, but also contributes to the development of effective monitoring and diagnostic techniques. Damage identification plays a vital role by providing timely damage assessment, which improves safety and maintains high performance and reliability for civil structures (Subhasmita, P., 2019).

The aim of this investigation is to find out the differences in the natural frequencies and mode shapes for several beam models, including a homogenous beam and a beam with a crack. To achieve this aim, the following tasks are defined:

Task 1: Obtaining the first five natural frequencies and mode shapes of an **ideal** (without any defects) pinned-rolled simply supported beam through analytical relations based on the theory of the Euler and Timoshenko beams.

Task 2: Obtaining the first five natural frequencies and mode shapes of a **FEM model** of the same ideal beam from **Task 1** in two cases:

- the supports are applied on the beam mid line, as it is supposed in the Euler and Timoshenko beam theory;
- and the supports are applied on the entire beam's surface, as it can be in the real fiscal couplings.

Task 3: Modeling of a **crack** into the above FEM model and performing linear modal calculations by stiffness and mass matrix. After that, performing a numerical impact test, obtaining and analyzing the free vibrations to determine the vibration spectrogram.

The object of this investigation is a straight beam with length of 200 mm. The beam has a solid quadratic cross section with dimensions 10x10mm. At the left end, the beam is pinned (hinged). At the right end, the beam is rolled. The "ideal" beam is homogenous, and has no holes or defects, like cracks for example. The "cracked" beam has a crack with depth of 2.5 mm and width of 0.002 mm, and ends with a round with radius of 0.001mm. The crack location is at the middle of the beam, but the impact force applying point varies with consideration of the nodes in the natural mode shapes of the beam. The crack is on the bottom beam side, and the impact force application point is on the top beam side.

2. FREQUENCY EQUATIONS OF PINED-ROLLED SIMPLY SUPPORTED BEAM

To derive the equations for **natural frequencies** of beams under the **Euler-Bernoulli** and **Timoshenko** beam theories, let's review the governing equations and assumptions in each theory.

In Euler-Bernoulli beam theory, cross-sections of the beam are assumed to remain perpendicular to its neutral axis and do not undergo any deformation during bending. This assumption neglects shear deformation and rotary inertia, making this theory **more accurate for slender, long beams**.

The equation of motion for transverse vibrations in a **Euler-Bernoulli beam** is given by (Quila, M., Sarkar, S., 2024):

$$\frac{\partial^2}{\partial t^2}(\rho A w(x, t)) + \frac{\partial^4}{\partial x^4}(EI w(x, t)) = 0, \quad (1)$$

where: $w(x, t)$ is the transverse displacement, E is the Young's modulus, I is the area moment of inertia, ρ is the material density, and A is the cross-sectional area.

The **Timoshenko beam** theory accounts for:

- Shear deformation, addressing the relative displacements in cross-sections,
- Rotary inertia, which considers the rotational motion of cross-sections.

This leads to the following modified equation of motion (Zhou, B., Bingham, H., Shao, Y., 2024):

$$\frac{\partial^2}{\partial t^2}(\rho A w(x, t)) + \kappa G A \frac{\partial^2 w(x, t)}{\partial x^2} = EI \frac{\partial^4 w(x, t)}{\partial x^4}, \quad (2)$$

where: G is the shear modulus, κ is the shear coefficient.

The main difference in frequencies between the two models arises from the inclusion of shear deformation and rotary inertia in Timoshenko theory. These factors have a pronounced effect on shorter, thicker beams and produce slightly lower natural frequencies compared to the Euler-Bernoulli model, especially in higher modes.

According to Eq. 1 and Eq. 2, the first five natural frequencies and mode shapes of the ideal beam investigated are calculated and presented on Fig. 1 and Table 1.

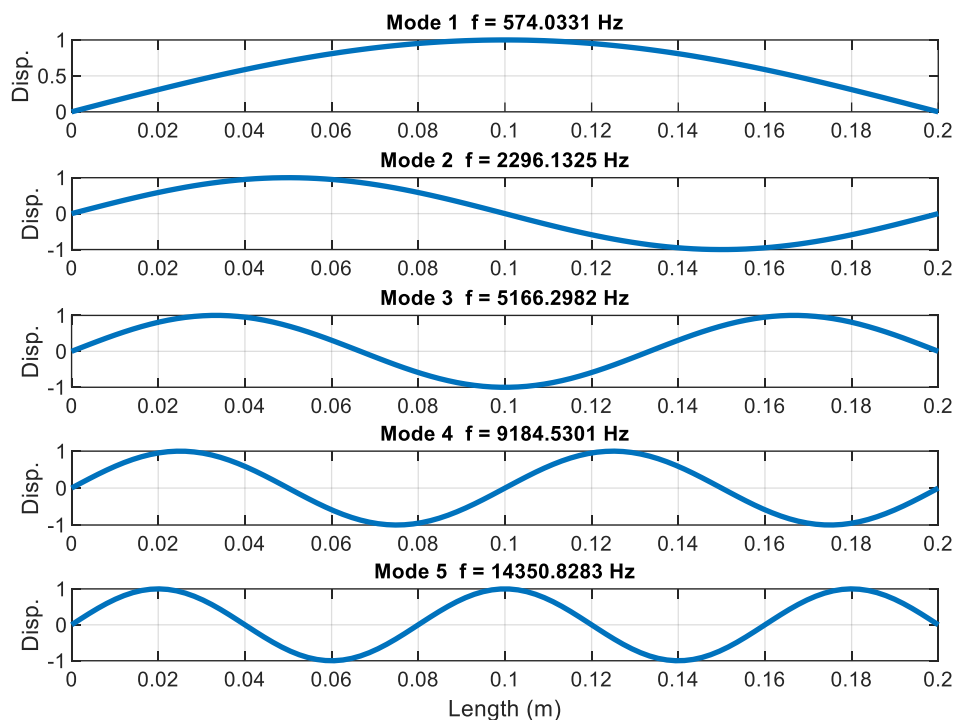


Fig.1. Natural frequencies and mode shapes according to Euler-Bernoulli theory

Table 1. Analytically obtained results for the ideal beam

Mode №	Natural frequency, Hz			
	Euler-Bernoulli Hz	Timoshenko Hz	Absolute difference Hz	Relative difference %
1	574	572	2	0.35
2	2296	2259	37	1.64
3	5166	4985	181	3.63
4	9185	8638	547	6.33
5	14351	13090	1261	9.63

3. FINITE ELEMENT LINEAR MODAL ANALYSIS OF THE IDEAL BEAM

Finite element analysis gives the opportunity to obtain results not only for a beam that is supported on its mid line, but also for supporting devices, which are mounted on the whole side section area. So, a comparison of the results obtained for these two cases is presented on the Fig. 2 and Fig. 3.

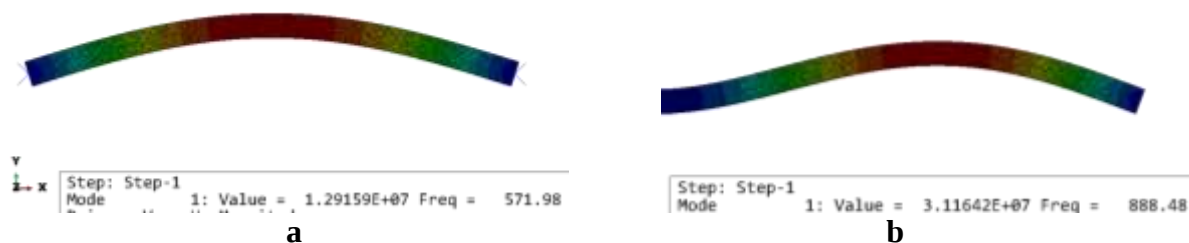


Fig. 2. The first natural frequency and mode shape of the investigated beam:
a – for mid line supports (572Hz), b – for whole side supports (888 Hz)

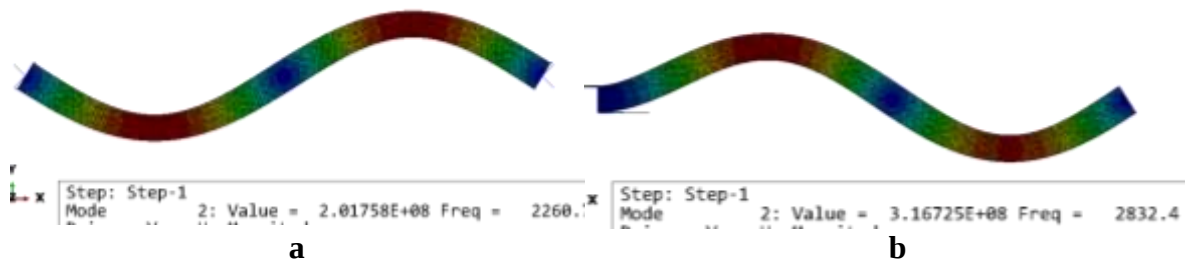


Fig. 3. The second natural frequency and mode shape of the investigated beam:
a – for mid line supports (2260 Hz), b – for whole side supports (2832 Hz)

It must be taken a decision which supporting scheme to be used for the basis results that will be compared with the results from the cracked beam. The choice is made on **the middle line supported case**, as this is the analytically comparative case, and also because this is the more commonly used option in general.

4. FINITE ELEMENT LINEAR MODAL ANALYSIS OF THE CREAKED BEAM

On Fig. 4 are presented the first five natural frequencies and mode shaped of the cracked beam, obtained through the modal analysis performed. One can notice that the crack may be opened or closed in the different mode shapes. In other words, for a given mode shape, the crack may be located at a node, and also it can be located in an antinode. The values of the natural frequencies are listed in Table 2, and the location of crack is also noted to compare the different cases. **The four natural frequency and mode shape corresponds to axial deformations and are not obtained in the analytical results presented above (Table 1).**

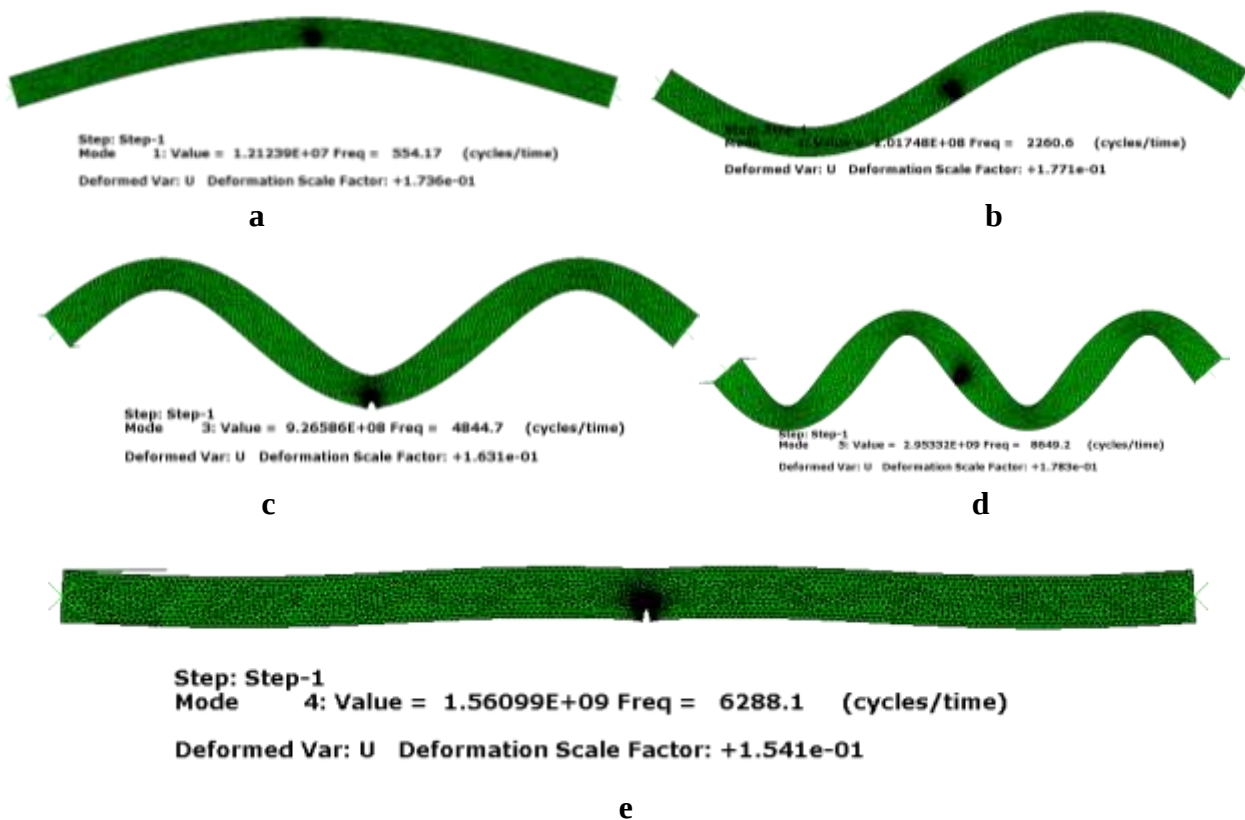


Fig. 4. The first five natural frequencies and mode shaped of the cracked beam:
a – the first natural frequency (554 Hz) and mode shape, b – the second natural frequency (2261 Hz) and mode shape, c – the third natural frequency (4845 Hz) and mode shape, d – the five natural frequency (8649 Hz) and mode shape, and e – the four frequency (6288 Hz) and shape

5. IMPACT TEST MODAL ANALYSIS

The impact force is applied at 140 mm from the left beam end, attempting to avoid the natural nodes (Fig. 1). The spectrogram obtained through Fast Fourier Transform for **the ideal beam free vibration acceleration** is shown on Fig. 5. The application impact force point is close to one of the nodes of the third mode shape, so this mode shape is excited very slightly. As a result, on Fig. 5 can be seen four peaks, as follows: **the first natural frequency of 567 Hz, the second – 2267 Hz, the four – 8666 Hz, and the five – 13166 Hz.**

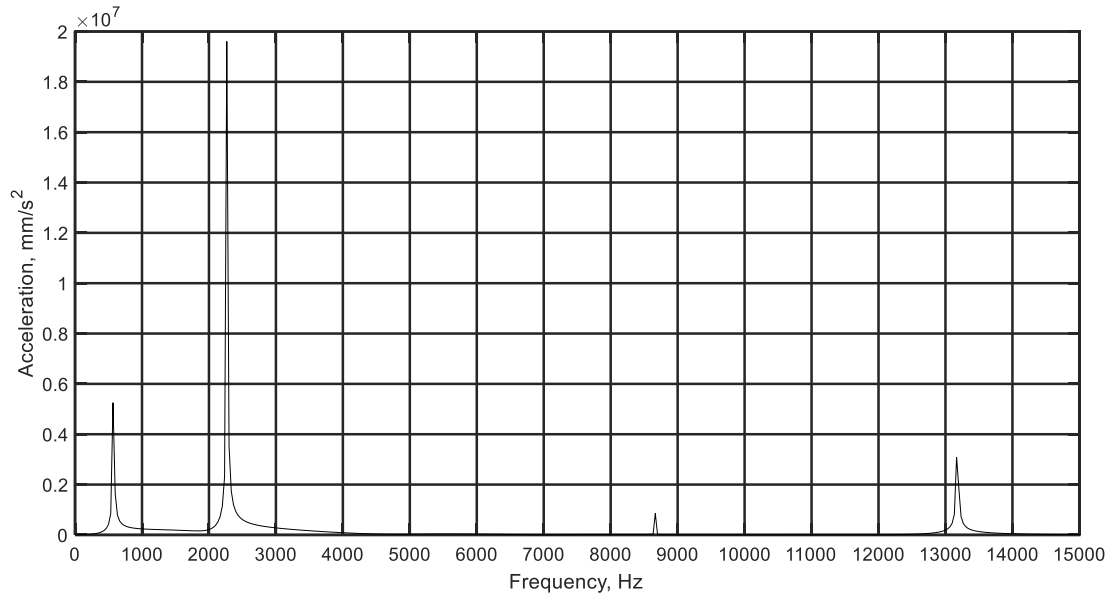


Fig. 5. A spectrogram from the impact modal test on the ideal beam

Other point also can be used as an impact force application point. For example, as the application point may be used the middle beam point at 100 mm. But this is an inappropriate option for this investigation, and the reason can be seen on Fig. 6. This investigation is interested from the nonlinear effects due the crack presence. On Fig. 6 is presented **the spectrogram for the cracked beam**. It can be seen that there are **two subharmonics** (at 12400 Hz and at 13532Hz) around the five natural frequency (at 12966Hz) in difference with the spectrogram of the ideal beam. As is known in scientific fields of nonlinear oscillations, the occurrence of such subharmonics is **an indication of the presence of nonlinearity** (Stoyanov S., 2015).

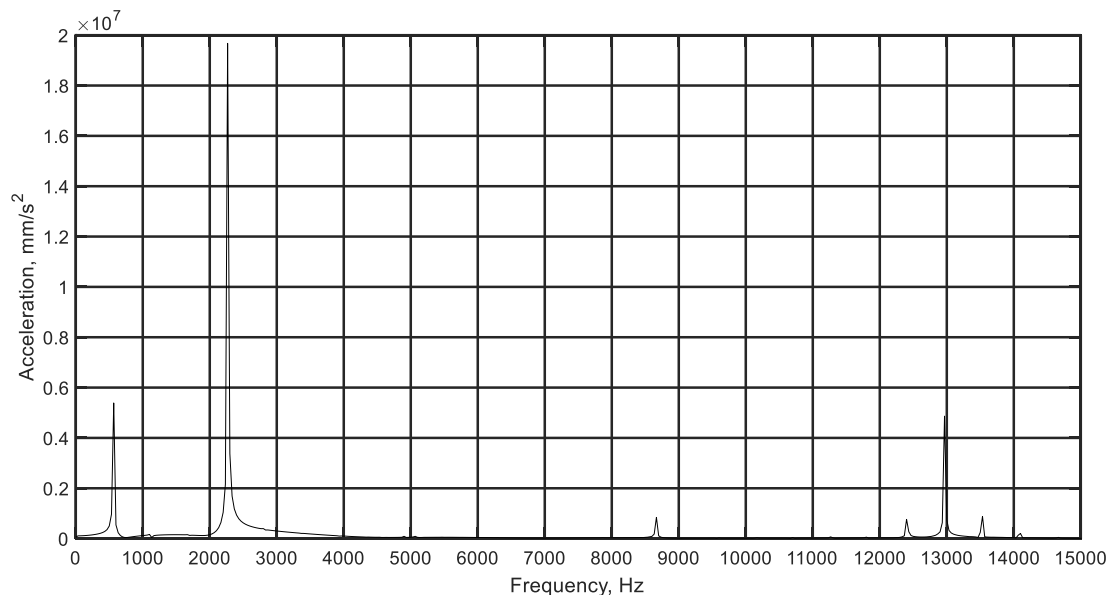


Fig. 6. A spectrogram from the impact modal test on the cracked beam

6. RESULTS AND CONCLUSIONS

The obtained results are summarized in Table 2.

Table 2. Results from the modal and impact tests

Natural mode №	Natural frequency					Crack Position
	Ideal beam, Linear modal Hz	Cracked beam		Ideal vs Cracked, modal		
		Linear modal Hz	Impact test Hz	Absolute difference Hz	Relative difference %	
1	572	554	567	18	3	In antinode
2	2261	2261	2267	0	0	In node
3	4990	4845	—	145	3	In antinode
4	6332	6288	—	44	0.7	In antinode
5	8650	8649	8666	1	0.01	In node

The planned tasks of this investigation are performed successfully. With the help of Table 2, one can observe that if the crack is located at mode shape antinode, there is a difference between the natural frequencies of the ideal and the cracked beam investigated. Also, the impact modal test performed indicates the presence of nonlinearity through two subharmonics in the free vibration acceleration spectrogram of the cracked beam. The presented in Table 2 data, show that there are still questions to clarify and the investigation should be continued and enhanced.

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DETERMINATION OF EFFICIENCY, METAL RECOVERY, DEPOSITION COEFFICIENT AND ARC STABILITY OF COATED ELECTRODES

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Abstract: Manual arc welding is one of the main methods for manufacturing welded structures due to its many advantages, such as low cost, mobility, ability to connect a wide variety of metal materials, etc. The welding results depend on both the qualification of the welders and the electrodes used. The work presents results for efficiency, metal recovery, deposition coefficient and arc stability of coated electrodes widely used in Bulgaria for welding low-carbon unalloyed and low-alloyed steels. The studies were conducted according to ISO 2401:2018.

Keywords: Coated Electrodes, Efficiency, Metal recovery, Deposition coefficient.

8. ВЪВЕДЕНИЕ

Ръчното електродъгово заваряване с обмазани електроди (eng. Manual metal arc welding) е един от най-често използваните методи за заваряване намерили приложение в практиката. Методът е с числов код 111 (ISO 4063:2023), а добавъчните материали са под формата на обмазани (покрити) електроди.

Една от основните класификации на обмазаните електроди е според типа на обмазките. Въз основа на това те биват четири основни групи: рутилови, базични, целулозни и рудно – кисели. От тях за заваряване на нисковъглеродни нелегирани и нисколегирани стомани (използвани широко за производство на заварени конструкции) основно се използват електродите с базични и рутилови обмазки.

От съществено значение при използването на обмазани електроди е поведението им по време на работа, а именно: стабилно горене на дъгата, скорост на стопяване, пръскоотделяне, възможност за работа в различни пространствени положения, производителност и т.н. (Mamatkulov, O., 2021; Smirnova, Zh., et al. 2020). Тези характеристики зависят основно от типа на обмазката и режимите на работа. За изследването им се определят рандемана на електрода (R_N , R_E , R_D , R_G), коефициентът на наваряване (D) и устойчивостта на горене на дъгата (Ferdinandov, N., 2023).

Целта на работата е свързана с определяне на рандемана, коефициента на наваряване и стабилността на горене на дъгата на определени марки обмазани електроди използвани често в България за заваряване на нисковъглеродни нелегирани и нисколегирани стомани.

9. ИЗЛОЖЕНИЕ

За провеждане на изследванията са избрани обмазани електроди с рутилов тип обмазки "R" (марки Вежен и Рожен) и с базичен тип обмазки "B" (марки Норд и Hard). Част от тях (Рожен и Hard) понастоящем се произвеждат в България в "Завод за Електроди" ООД, гр. Ихтиман, а другата част (Вежен и Норд) са електроди, които са създадени и дълго произвеждани в България, но за съжаление сега производството им е изнесено в чужбина.

Изследванията на рандемана и коефициента на наваряване са съобразени изцяло и проведени съгласно препоръките на сега действащите стандарти (ISO 2401:2018). Определянето на стабилността на горене на дъгата е описано в (Ferdinandov, N., 2023).

Означенията (ISO 2560:2020) на изследваните марки електроди са представени в таблица 1, а програмата на изследване в таблица 2.

Таблица 1. Означения на изследваните марки електроди

Марка	Диаметър, mm	Означение съгласно EN
Норд	ø 3,2	E 46 5 B 3 2 H5
Норд	ø 2,5	E 42 4 B 3 2 H5
Hard	ø 2,5 и ø 3,2	E 42 5 B 4 2 H5
Вежен	ø 2,5 и ø 3,2	E 42 0 RR 1 2
Рожен	ø 2,5 и ø 3,2	E 38 0 RR 1 2

Съгласно тези означения числата 1, 3 или 4 (намиращи се след буквеното означение на типа на обмазките – RR или B) показват номиналния рандеман на електрода при постоянен и променлив ток.

Съответно 1- $\leq 105\%$ при DC и AC,

3- $\geq 105\% \leq 125\%$ при DC и AC;

4- $\geq 105\% \leq 125\%$ при DC;

Таблица 2. Програма на изследване

Тип обмазка	Марка на електрода	Диаметър на електрода	Параметри на режима по каталог	Полярност	Режим на изследване
Базична	Норд	ø 2,5	70-110	DC+	99A
		ø 3,25	110-140	DC+	126A
Базична	Hard	ø 2,5	60-80	DC+	72A
		ø 3,25	80-120	DC+	108A
Рутилова	Вежен	ø 2,5	50-110A	AC ~	99A
		ø 2,5	50-110A	DC-	99A
		ø 3,25	80-150A	AC ~	135A
		ø 3,25	80-150A	DC-	135A
Рутилова	Рожен	ø 2,5	60-90	AC ~	81A
		ø 2,5	60-90	DC-	81A
		ø 3,25	80-140	AC ~	126A
		ø 3,25	80-140	DC-	126A

За определяне на рандемана и коефициента на наваряване са използвани формулите по-долу:

$$R_N = \frac{md}{m_{cn}} \cdot 100, \% \quad (1) \quad R_E = \frac{md}{m_{ce}} \cdot 100, \% \quad (2) \quad R_G = \frac{md}{m_e} \cdot 100, \% \quad (3)$$

$$R_D = \frac{md}{m_e - m_s} \cdot 100, \% \quad (4) \quad D = \frac{md}{I_m \cdot t}, g / A \cdot \min \quad (5)$$

Където:

m_d - маса на навареният метал, g

m_{cn} – маса на металните сърцевини на 5-те електрода, g

m_{ce} - маса на изразходваните метални сърцевини на 5-те електрода (без остатък), g

m_e – маса на изпитваните 5 електрода с обмазката, g

m_s – маса на остатъците от изпитваните 5 електрода с обмазката, g

t - време на горене на дъгата, min

I_m – сила на тока при наваряването, А

R_N – рандеман на електрода с остатъка (метална пръчка + обmazка), %

R_E – рандеман на електрода (метална пръчка + обmazка) без остатъка, %

R_G – рандеман на металната пръчка на електрода без остатъка, %

R_D – рандеман на металната пръчка на електрода с остатъка, %

D- коефициент на наваряване, g/A.min

Останалите изисквания и условия свързани с провеждане на изследванията са описани и представени в (Ferdinandov, N., 2023).

Заваръчният токоизточник е от инверторен тип – TIGER 210 AC/DC с възможност за работа както с променлив, така и с постоянен ток.

РЕЗУЛТАТИ

Резултатите от проведените изследвания са представени в таблица 3 и на фигурите по-долу.

Таблица 3. Резултати от изследването

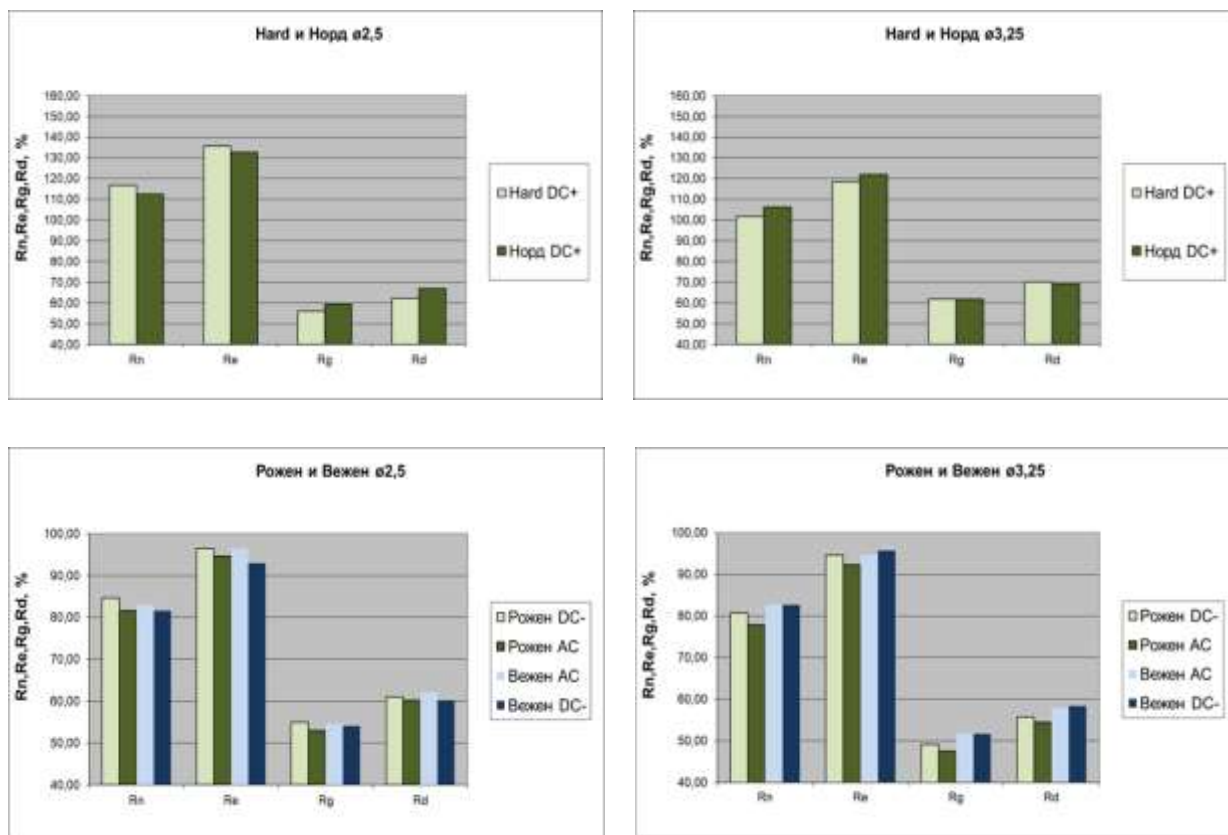
Марка на електрода	Диаметър на електрода, mm	Големина на тока I_m , А	Полярност на свързване	Рандеман на електрода с остатъка R_N , %	Рандеман на електрода без остатъка R_E , %	Рандамен на металната пръчка на електрода без остатъка R_G , %	Рандамен на металната пръчка на електрода с остатъка R_D , %	Коефициент на наваряване D, g/A. min	Стабилност на горене на дъгата, mm
Рожен	ø2,5	81	DC-	84,62	96,49	55,00	61,11	0,16	14
Рожен	ø2,5	81	AC~	81,54	94,64	53,00	60,23	0,14	13
Рожен	ø3,25	126	DC-	80,73	94,62	49,16	55,70	0,14	13
Рожен	ø3,25	126	AC~	77,98	92,39	47,49	54,49	0,12	11
Вежен	ø2,5	99	DC-	81,54	92,98	54,08	60,23	0,14	13
Вежен	ø2,5	99	AC~	83,08	96,43	54,55	62,07	0,13	12
Вежен	ø3,25	135	DC-	82,73	95,79	51,70	58,33	0,14	16
Вежен	ø3,25	135	AC~	82,73	94,79	51,70	57,96	0,12	11
Hard	ø2,5	72	DC+	116,92	135,71	55,88	62,30	0,16	8
Hard	ø3,25	108	DC+	101,77	118,56	61,83	70,12	0,16	10
Норд	ø2,5	99	DC+	112,31	132,73	59,35	66,97	0,15	10
Норд	ø3,25	126	DC+	106,36	121,88	61,90	69,23	0,16	8

Вижда се, че рандемана R_N и R_E (с и без отчитане на остатъка) зависи основно от типа на обmazката.

Електродите с базичен тип обmazка притежават рандеман над 100% (фиг. 1). Максимални стойности са налице при електроди „Норд” и „Hard” с диаметър Ø2,5mm, като достига $R_E=133\%$, $R_N=112\%$ и съответно $R_E=136\%$, $R_N=117\%$ (без и с отчитане на остатъка). Причината е в съдържащите се метални прахове в състава на обmazките, които служат за допълнително легиране на метала на шева.

Прави впечатление, че при електродите „Норд” и „Hard” с диаметър Ø3,25mm отчетените стойности за рандемана са по-малки от тези при електродите с диаметър Ø2,5mm. Тук една от причините е различната дебелина на обmazките. При електродите „Hard” с диаметър Ø3,25mm дебелината на обmazката е около 70% от диаметъра на металната пръчка, докато при тези с

диаметър Ø2,5mm е 100% диаметъра на пръчката. При електродите „Норд“ с диаметър Ø3,25mm дебелината на обмазката е около 78% от диаметъра на металната пръчка, докато при тези с диаметър Ø2,5mm е 85% диаметъра на пръчката.



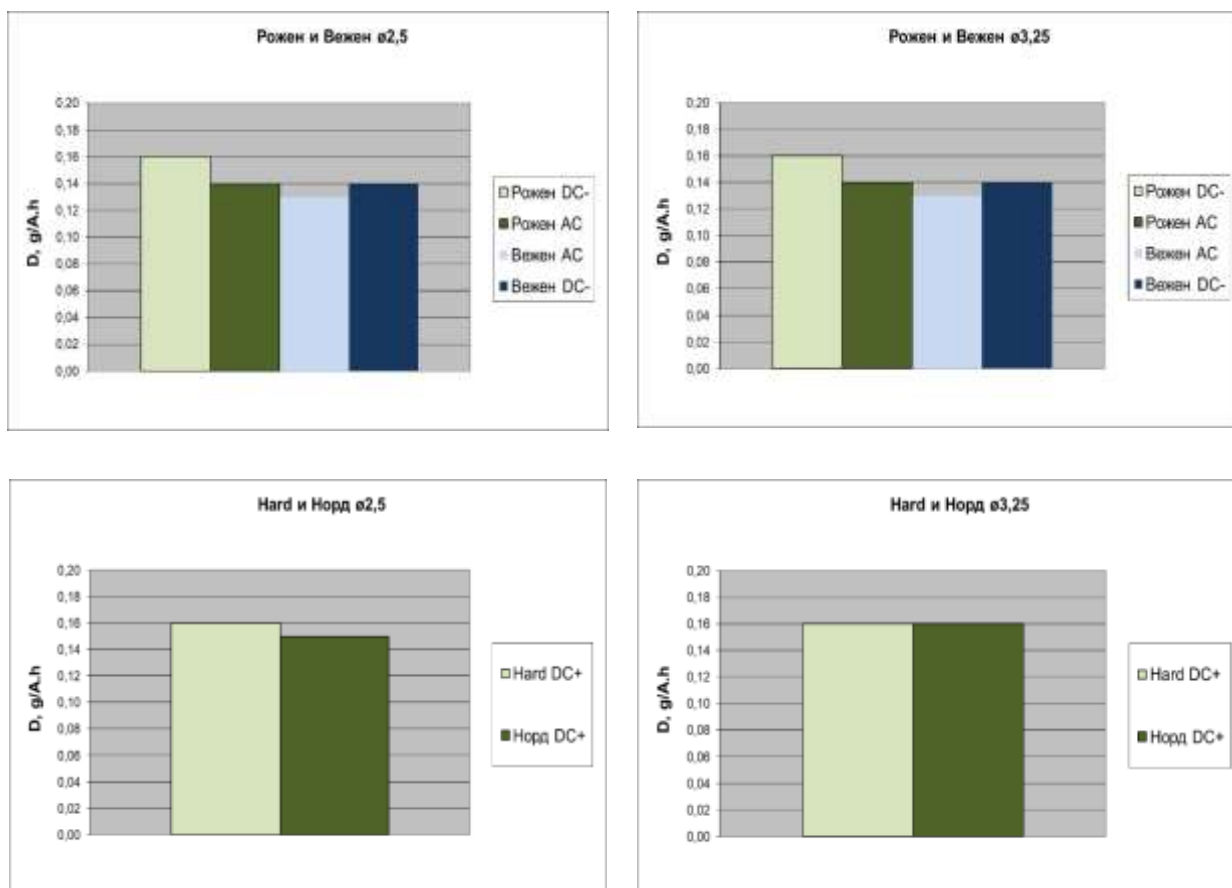
Фиг. 1. Рандеман на изследваните обмазани електроди

При електродите с рутилов тип обмазка (фиг. 1) рандемана във всички случаи е под 100% поради наличието на загуби, вследствие пръскообразуване и изпаряване на част от металната пръчка в зоната на горене на дъгата. При „Рожен“ той достига до $R_E=96,5\%$ (94,6 %), $R_N=84,6\%$ (81,5%) при диаметър Ø2,5mm и $R_E=94,5\%$ (92,4%), $R_N=80,7\%$ (78%) при диаметър Ø3,25mm. При електродите „Вежен“ рандемана е в рамките до около $R_E=93\%$ (96,4%), $R_N=81,5\%$ (83%) при диаметър Ø2,5mm и $R_E=95,8\%$ (94,8%), $R_N=82,7\%$ (82,7%) при диаметър Ø3,25mm.

Макар и значително по-малко, върху рандемана влияние оказва и вида на тока. При използването на постоянен ток и права полярност на свързване (DC-), той е по-висок в сравнение с този получен при използване на променлив ток (AC). Това е в сила (с едно изключение) независимо от диаметъра на електродите.

Резултатите за рандемана на металните пръчки на всички марки изследвани електроди (R_G и R_D) с диаметър Ø 2,5mm са от един порядък с изключение на електродите марка „Норд“, където те са с около 4÷5% по-високи. При тези с диаметър Ø 3,25mm получените резултати показват по-високи стойности при базичните електроди в сравнение с рутиловите.

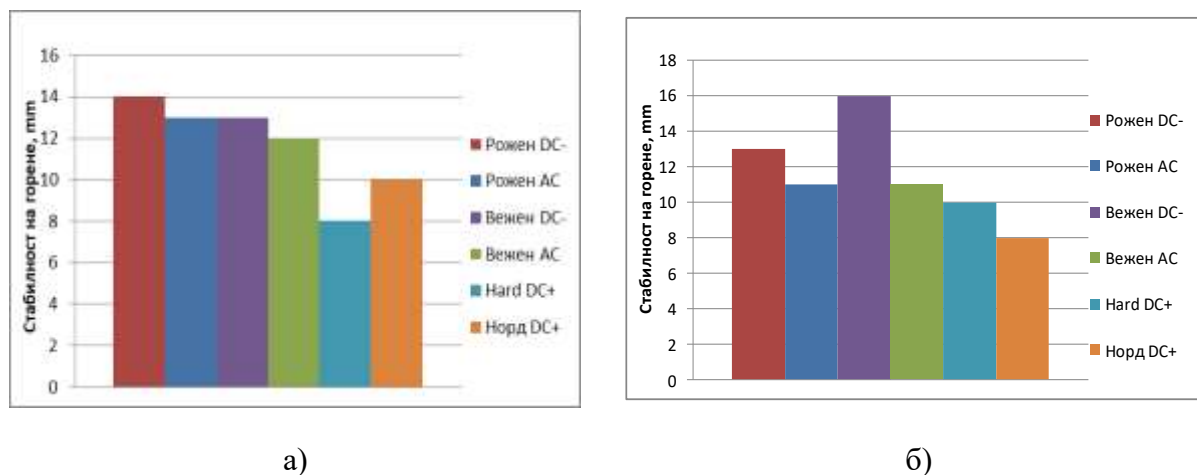
И при двата диаметъра на електродите с базичен тип обмазка (Норд и Hard) коефициентът на наваряване (фиг. 2) е постоянен и като цяло по-висок от този при електродите с рутилова обмазка (Вежен и Рожен). При тези с рутилов тип обмазка се установяват по-високи стойности за коефициента на наваряване при работа с постоянен ток в сравнение с използването на променлив.



Фиг. 2. Коефициент на наваряване на изследваните обмазани електроди

Резултатите по отношение на стабилността на горене на дъгата са показани на фигура 3. При електродите “Рожен” и “Вежен” с рутилов тип обмазка тя е видимо по-голяма в сравнение с електродите “Hard” и „Норд“ с базичен тип обмазка. Причината е наличието на TiO_2 (основен компонент в рутиловите обмазки), който осигурява много стабилно горене на дъгата.

Макар и по-малко влияние оказва и вида на тока, като при използване на постоянен ток с права полярност на свързване стабилността е по-висока от случая, в който се използва променлив ток.



Фиг. 3. Стабилност на горене на дъгата на изследваните обмазани електроди с диаметър Ø2,5mm (а) и Ø3,25mm (б)

10. ЗАКЛЮЧЕНИЕ

Резултатите от изследванията показват, че върху рандемана, коефициента на наваряване и стабилността на горене на дъгата на обмазаните електроди за ръчно електроудгово заваряване основно влияние оказва типа на обмазката. Базичните обмазки осигуряват по-висок рандеман и коефициент на наваряване, за сметка на стабилността на горене на дъгата, която значително отстъпва на тази при електродите с рутилови обмазки.

При електродите с рутилов тип обмазки е установено, че върху изследваните характеристики влияние оказва и вида на тока. Използването на постоянен ток, права полярност на свързване в сравнение с променлив ток води до повишаване както на рандемана и коефициента на наваряване, така и на стабилността на горене на дъгата.

11. БЛАГОДАРНОСТИ

Публикацията е финансирана по проект 2024-ФМТ-01 "Разработване и изследване на цифрови технологични методи"

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ELECTROLITIC ETCHING OF A 12CR18NI10T STAINLESS STEEL¹

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Abstract: Weldments of a NO_x abator made of austenitic stainless steel 12Cr18Ni10Ti have been tested on intergranular corrosion after working for more than 10 years at a temperature of 500°C and pressure of 1.16 MPa. Corrosion damage like knife-line attacks were observed leading to the need for testing for electrochemical corrosion. Weldments were subjected to anodic polarization up to potentials where transpassive dissolution occurred. After the electrochemical tests in 5% vol. H₂SO₄ water solution, open to air at room temperature, the tested surfaces were metallographically observed, and it turned out that 12Cr18Ni10Ti steel had kept its resistance to intergranular attacks. Metallographic examinations revealed that high temperatures lead to a less commonly encountered form of corrosion - chemical corrosion, manifested as high-temperature oxidation of grain boundaries. Nevertheless, electrochemical testing in sulfuric acid water solution proved to be a suitable method for etching the microstructure of the stainless steel, as good as chemical etching. As an advantage of electrochemical etching with the used acidic solution, the simultaneous revealing of austenitic grains and chromium carbides can be pointed out, eliminating the need for application of several chemical reagents for etching all macrostructure's constituents.

13. ВЪВЕДЕНИЕ

При определени условия на експлоатация, съчетани с неблагоприятно фазово и структурно състояние, неръждаемите стомани претърпяват локални видове корозия. Най-често това са поражения във вид на питингова, процепна и междукристална корозия. Процесите, водещи до тези корозионни разрушения, имат електрохимичен характер (Rwmd, et al., 2009). Това обяснява и защо са най-широко срещаните при неръждаемите стомани. Изобилието от вода и водни пари в околната среда, в които са разтворени различни йони, предоставя електролит за осъществяване на корозионни процеси. Въпреки наличието му обаче, корозионните явления биха могли да се възпрепятстват, ако фазовият състав и структурата на неръждаема стомана не позволяват образуване на свързани накъсо анодни и катодни участъци.

Поради неправилно термично обработване, или поради неподходящи условия на експлоатация, в неръждаемите стомани е възможно да се отделят карбиди на хрома, който е основен легиращ елемент в тези стомани. Независимо от структурния клас на стоманата, карбидите се образуват по границите на зърната на твърдите разтвори (α или γ). Това разположение на хромовите карбиди е обусловено от различните скорости на дифузия на хрома и на въглерода в твърдите разтвори. Така, малките, бързоподвижни атоми на въглерода успяват да изминат пътя от обема на зърната до границите им. Хромовите атоми успяват да изминат едва няколко междуатомни разстояния, за да се свържат с въглеродните по границите на зърната. Там, поради повишеното енергийно ниво, дължащо се на голямото количество несвършенства в кристалния строеж, процесите на образуване на нови фази са улеснени. Така границите на зърната на твърдите разтвори се оказват обеднели на хром, при което губят способността си да се пасивират, а електродният им потенциал се измества в отрицателна посока. Тези пригранични, бедни на хром области, са в непосредствен контакт с карбидите на хрома, за които е известно, че имат положителен електроден потенциал в различни среди. В резултат, по границите на зърната се образуват микрогалванични корозионни елементи, при работата на които се наблюдава междукристална корозия (Chung & Szklarska-Smialovska, 1981), (Dabossi, et al., 1994).

¹ Докладът е представен на пленарната сесия на 27 октомври 2016 с оригинално заглавие на български език: ПРИЛАГАНЕ НА АКТИВНИ МЕТОДИ ЗА СЕИЗМИЧНА ЗАЩИТА

Образуването на карбидите на хрома (Cr_{23}C_6) в неръждаемите стомани се извършва най-интензивно в температурния интервал от 500°C до 850°C , който е и неблагоприятният от корозионна гледна точка интервал на експлоатацията им. При наличие на достатъчно количество легиращ елемент с по-голям афинитет към въглерода от хрома, образуването на хромовите карбиди може да бъде възпрепятствано. За това обаче е нужно предварително стоманата да е приведена във фазово състояние, включващо и карбидите на този легиращ елемент. Най-често като такъв легиращ елемент се използва титанът, а в някои случаи - и ниобият. Карбидите на титана са устойчиви до температури под 1050°C , а над тази температура се разтварят в твърдите разтвори. Ако при следващо охлаждане не е осигурено достатъчно време за отделянето им при температури над 850°C , то титанът от тях остава в твърдия разтвор, и не успява да изпълни предназначението си като легиращ карбидообразуващ елемент. Това е определило и коректните режими за термично обработване на неръждаеми стомани с цел предотвратяване на междукристална корозия (Рашков, 1993).

14. ИЗЛОЖЕНИЕ

Методика на експеримента

Целта на експеримента е да се установи приложимостта на електрохимичен метод за определяне на склонността на неръждаема стомана към междукристална корозия и за едновременно проявяване на микроструктурата на стоманата (Habraken, 1966).

Изследвана е стомана 12X18H10T, използвана като корпус на пречиствател на азотни оксиди, работил циклично повече от едно десетилетие при температура 500°C . Съставът на стоманата по стандарта ГОСТ 5632-72 в масови проценти е: до 0.12 % C, до 0.8% Si, до 2% Mn, 9...11% Ni, 17...19% Cr, 0.2...1% Ti.

Съществуват редица стандартизирани процедури за изследване на склонността на неръждаеми стомани към междукристална корозия (ASTM, 2015). Някои от тях са описани в стандартите ASTM 262 и ГОСТ 6032. Тези процедури са трудни за изпълнение, с голяма продължителност, изискват работа с кипящи разтвори на киселини. Заради това в представения тук експеримент е използван електрохимичен метод за определяне на склонността на стоманата към междукристална корозия. Тестовите са извършени в 5 об.% H_2SO_4 воден разтвор.

Известно е, че за склонността към междукристална корозия може да се съди по вида на анодните потенциодинамични криви (Talbot & Talbot, 1998). Поради това, в посочената горе среда, е извършена външна поляризация на образци от стомана 12X18H10T. Използван е потенциостат RADELKIS OH405, свързан към компютър с помощта на дигитален контролер на National Instruments USB 6008. Тестваните образци са разположени в стандартна триелектродна клетка с Pt-противоелектрод и наситен каломелов електрод като сравнителен. Стойностите на докладваните потенциали са преизчислени спрямо стандартен водороден електрод при отчитане на температурата.

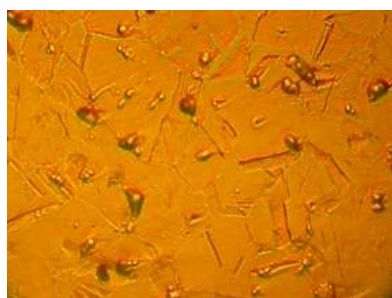
Изследвани са образци, отрязани успоредно и нормално на направлението на валцоване. Образците са предварително шлифовани, полирани (Al_2O_3 0.03 μm) и почистени с ацетон. Преди поляризацията, пробите са оставени в електролита да се стабилизират до достигане на стационарна стойност E_{ss} на свободния потенциал. Времето за това е около 60 min. След това, образците са анодно поляризирани от начален потенциал с 250 mV по-отрицателен от стационарния. С цел достигане на областта на транспасивно разтваряне, крайният потенциал на външната поляризация е 1590 mV. Скоростта на разгъване на потенциала е 1mV/s. За определяне на склонността към междукристална корозия на образците е извършено анодно разтваряне чрез потенциостатиране. Потенциостатирането е приложено веднага след достигане на потенциала от 1590 mV, и е с продължителност 10 min.

Извършено е и химично проявяване на стоманата. Проявени са образци, срязани успоредно на направлението на валцоване. След шлифване, полиране и подсушаване, образците са проявени с два реактива: 1) реактив на Мураками (10 g NaOH, 10 g червена кръвна сол, 100 ml

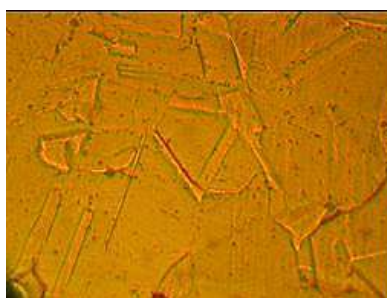
dH₂O) с температура 60°C за 120 s и 2) 20.3 g FeCl₃, 12.5 ml HCl, dH₂O 200 ml за 40 s (съкратено в текста реактив FeCl₃).

Електрохимично тестваните повърхности и химично проявените повърхности са наблюдавани с оптичен микроскоп EPITYP 2, снабден с цифрова камера.

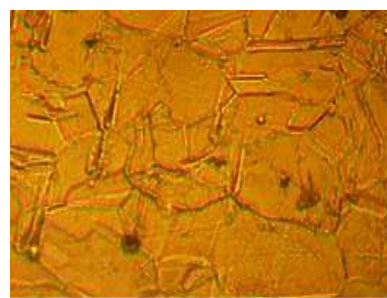
Разядените след потенциостатирането повърхности са сравнени с по-рано третирани по същия начин образци от неръждаема стомана AISI 321 със следния състав в масови проценти, определен чрез микро-рентгеноспектрален анализ със сканиращ електронен микроскоп JEOL SUPER PROBE 733: 17.83%Cr, 10.47%Ni, 1.09%Mn, 0.67%Ti. Тези по-рано електрохимично тествани в същата среда образци предварително са били подложени на различни видове термично обработване с цел установяване влиянието му върху склонността към междукристална корозия (Пиева, 2022). Режимите на термично обработване са: 1) закаляване от 1050°C за 20 min и охлаждане във вода; 2) провокиращо междукристална корозия отгряване за 60 min при 650°C и охлаждане на въздух; 3) стабилизиращо отгряване при 850°C за 30 min и охлаждане на въздух. Разядените повърхности са показани на фигура 1, откъдето се вижда, че междукристалната корозия се проявява във вид на удебелени граници между кристалните зърна на отгрития при 650°C образец. Подробно тълкуване на наблюдаваните на фигура 1 повърхности е дадено в (Пиева, 2022).



а) стомана AISI 321,
закалена от 1050°C във
вода, x500



б) стомана AISI 321,
отгрята при 850°,
охлаждане на въздух, x500



в) стомана AISI 321, отгрята
при 650°, охлаждане на
въздух, x500

Фигура 1. Потенциостатирани повърхности на аустенитна неръждаема стомана след различно термично обработване (Пиева, 2022)

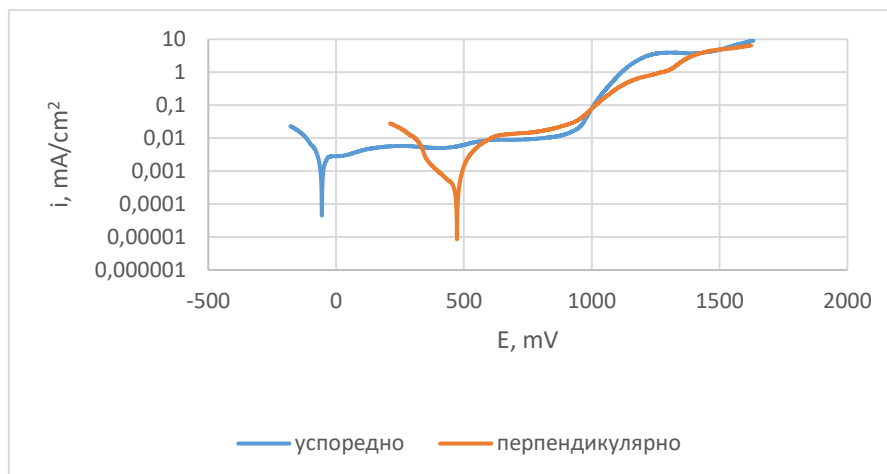
Резултати

На фигура 2 са показани получените потенциодинамични криви на външна анодна поляризация на тестваните образци, а на фигура 3 – промяната в плътността на тока по време на анодното разяждане. В таблица 1 са обобщени електрохимичните характеристики на стоманата в двете взаимно перпендикулярни направления.

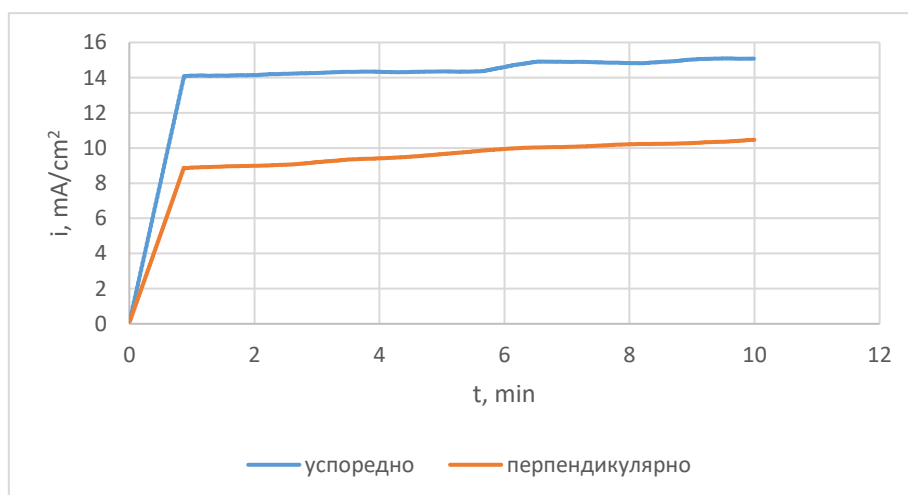
Таблица 1. Някои електрохимични характеристики на стомана 12X18H10T в 5% H₂SO₄

Тествана повърхност	E _{ss} , mV	E _{corr} , mV	i _{corr} , mA/cm ²
успоредна повърхност	81.44	-55.17	8,05x10 ⁻⁵
перпендикулярна повърхност	475	363.11	1,37x10 ⁻³

E_{ss} – стационарен потенциал; E_{corr} – потенциал на корозия, определен от потенциодинамичните криви; i_{corr} – плътност на тока на корозия, определена от потенциодинамичните криви



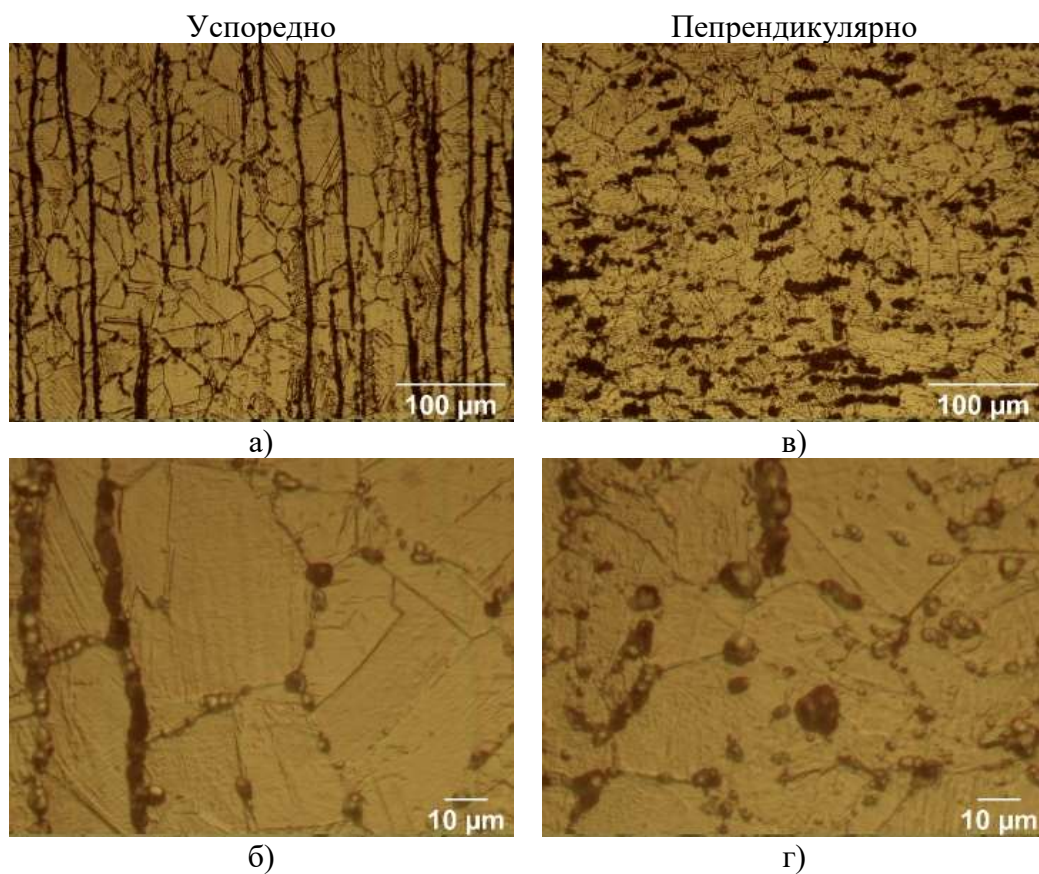
Фигура 2. Потенциодинамични криви на външна анодна поляризация на стомана 12X18H10T в 5% H_2SO_4



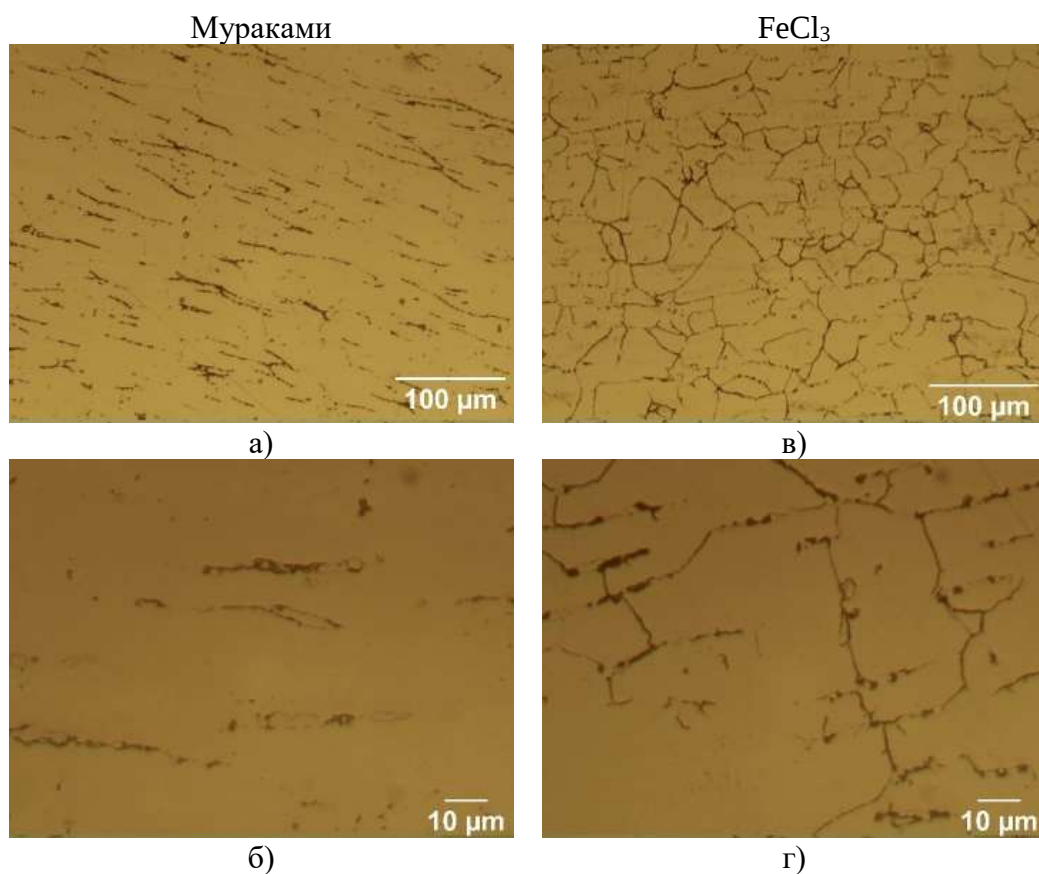
Фигура 3. Плътност на тока по време на потенциостатирание на стомана 12X18H10T в 5% H_2SO_4

Резултатите от електрохимичните експерименти показват електрохимична анизотропия на стоманата. От фигура 4 е ясно, че тя се дължи на разликата във формата и разположението на кристалните зърна в направление, успоредно на валцоването, и в направление, перпендикулярно на валцоването. Очевидно повърхността, върху която зърната излизат удължени по направление на пластичното деформиране, е с по-ниска устойчивост на обща електрохимична корозия. Черните ивици на фигура 4 представляват δ -ферит. При по-голямо увеличение (фигура 4 б) се вижда, че са се образували и корозионни ямки. Перпендикулярно на валцоването, зърната и на аустенита, и на ферита, изглеждат равноосни (фигура 4в и 4г), т.е. предоставят по-малко гранични области, в които анодното разтваряне е улеснено.

Сравнението на фигура 4 с фигура 1 показва, че стоманата не е склонна към междукристална корозия – и в двете направления аустенитните кристали са очертани – наблюдава се релеф от избиращелно разяждане на различно ориентираните зърна, а част от границите са слабо разтворени, но не и удебелени.



Фигура 4. Потенциостатирани повърхности



Фигура 5. Химично проявени повърхности

След потенциостатирането, образци от стоманата, срязани в направление, успоредно на валцоването, са проявени химично. Проявените повърхности са показани на фигура 5. Реактивът на Мураками оцветява карбидите и нитридите на хрома в светло жълто. От фигура 5а и 5б се вижда, че такива в стоманата липсват, разядени са само удължените феритни зърна, и то по-слабо, отколкото при потенциостатирането. Проявяването с реактива, съдържащ FeCl_3 , разкрива аустенитите зърна, и съвсем слабо – удължените феритни, както това се вижда от фигура 5в и 5г. При мислено наслагване на фигура 5а и 5в, както и на 5б и 5г, една върху друга, се формират картини, подобни на микроструктурите от фигура 4а и 4б, но без корозионните ямки. Това потвърждава, че потенциостатирането може да бъде използвано с две цели – 1) оценяване на склонността към междукристална корозия и 2) електрохимично проявяване на неръждаема стомана.

15. ЗАКЛЮЧЕНИЕ

Използването на предложения метод за оценяване на склонността към междукристална корозия на неръждаема стомана съкращава времето за изследване, тъй като едновременно с оценка на корозионното поведение проявява и микроструктурата. Известен факт е, че неръждаемите стомани са трудни за химично проявяване. Анодното разяждане чрез потенциостатиране обаче преодолява тази трудност, като едновременно с това премахва необходимостта от прилагане на няколко химични проявителя, които разкриват различни структурни съставки на неръждаемата стомана.

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MODERN METHODS FOR FABRICATION OF ULTRAFINE-GRAINED METAL SHEETS

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Abstract: For the past 35 years, the topic of ultrafine-grained materials and their production has been compelling researchers to explore further. A short summary of some of the most feasible methods of ultrafine-grained sheet metal production has been carried out.

Keywords: ultrafine-grained materials; severe plastic deformation; asymmetric rolling; cryorolling; accumulated roll-bonding; repeated corrugation and straightening.

INTRODUCTION:

In material science, ultrafine-grained (UFG) materials, defined as polycrystalline materials with grain size between 100 and 1000 nm [1], have attracted increased interest towards them because of their potential application in a multitude of industries and their importance to society. Thanks to the increased homogeneity of their microstructure, they possess improved physical-mechanical properties, compared to conventional materials, examples of which are higher tensile strength, fatigue wear resistance and hardness [2] [3] strength to strain ratio [4], as well as the ability to enter a state of superplasticity under specific circumstances [5].

Despite over 35 years of research in the field and the proven benefit of the UFG structure, its fabrication outside of laboratory conditions still presents a significant technological obstacle to the introduction of such materials in modern industry, hence the insufficient familiarity with such materials among the general public and industry professionals.

It is possible to produce materials possessing UFG structure via chemical synthesis methods (bottom-up method), but from an engineering standpoint, the more interesting approach is the method of fabrication via undergoing of severe plastic deformation (SPD) (top-down method), which generates shearing stresses under the large forces the material is being subjected to, leading to grain refinement on a microstructural level. In order to achieve the desired effect, it is necessary for the plastic deformation to reach 600% - 800%, which is possible by subjecting the materials multiple times to SPD [6].

Depending on the type of UFG samples produced, SPD methods are conditionally divided into three groups:

- discrete.
- semi-continuous.
- continuous – used for fabrication of sheet metals, plates and profiles.

This article aims to familiarize the reader with the continuous methods for UFG sample production and those concerning sheet metals in particular. Furthermore, those approaches selected are the ones with the highest potential for utilization at manufacturing scale. Most of the processes described are modifications of the existing one of rolling, granted its efficiency in sheet metal processing as well as the possibility to exert forces with high magnitude onto the material, generating the necessary shearing stress as a result, leading to the desired refinement of the material structure.

AREAS OF APPLICATION OF UFG METAL MATERIALS

UFG materials and their deriving products are commercially viable because of their increased mechanical and physical properties and their efficient production [7] [8], thus their potential application is broad.

In the biomedical sphere, UFG materials are used for non-integrated medical devices, shown in Figure 1 and especially in medical implants [9], where the increased strength and hardness of the material allow production of more durable, stronger and/or lighter prostheses. Furthermore, the finer the microstructure of the material, the better detail of the produced part, which is beneficial to small implants.



Figure 1: Non-integrated medical devices, produced from UFG Titanium [9]

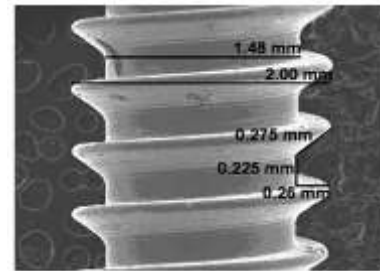
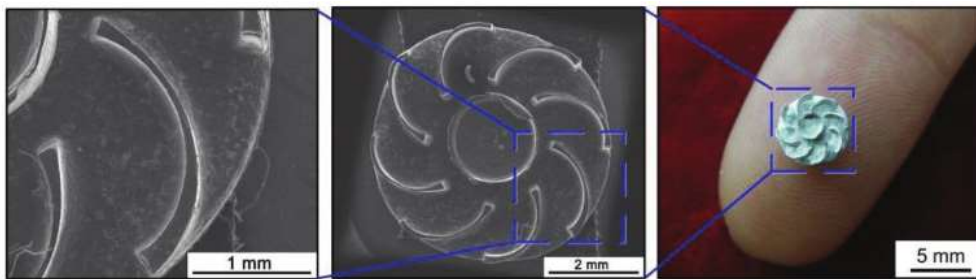


Figure 2: Dimensions of a miniscrew for orthodontic Anchorage, made of UFG material [9]

To further carry on to the advantage of the finer grain microstructure of UFG materials that they can be used in microforming applications is that they allow the possibility of production of parts which detail is smaller than that of the grain size of conventional materials. An example is given on Figure 3, where a microturbine is formed from an ultrafine-grained piece of aluminium [10].



3: Microturbine of UFG Aluminium [10]

In addition to miniature components, UFG materials could be extensively used in manufacturing of construction materials, such as fasteners – the stronger material will improve the quality of the fasteners. Furthermore, the higher wear resistance would be beneficial to manufacturing of construction profiles and different types of chassis, which can further be subjected to weight optimization, as the material would allow it. Wear resistance of UFG materials would make them an ideal choice for consumer products where the improvement in lasting appearance will be appreciated and necessary.

All these possible applications are valid for sheet metals as well, as their multi-purpose utilization can benefit from the superior mechanical properties of UFG materials

METHODS FOR FABRICATION OF UFG SHEET METAL SAMPLES

Asymmetric Rolling (AR)

Asymmetric Rolling is a modification of conventional rolling process, also known as symmetric rolling and is one of the most popular means of producing materials with ultrafine-grained microstructure. The rolling asymmetry is expressed in one or in combination of three ways:

- feeding the sample between rolls with different diameters, shown in Figure 4.
- feeding the sample between rolls with different angular velocities, shown in Figure 5.
- feeding the sample between rolls with different friction coefficients

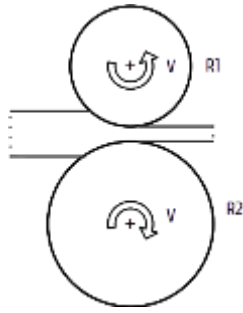


Figure 1: Asymmetric rolling via different diameters of the rolls

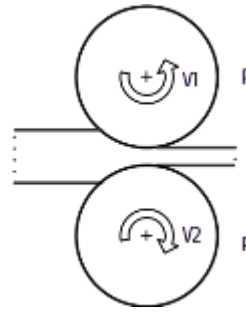


Figure 2: Asymmetric rolling via different angular velocities of the rolls

The difference in those three technological parameters is the premise for irregular deformation of the rolled sheets as the shearing stress is larger in those layers of the material that come in contact with the rolls possessing greater diameter, angular speed and/or coefficient of surface friction. It is experimentally proven that a combination of the three leads to better results than if only one of the techniques is used.

It is shown via experimental means that in asymmetric rolling of pure aluminium (Figure 6), if a reduction of 90% of the specimen's thickness is achieved, there is an increase of its tensile strength in approximately 2/3 times more than if the specimen was subjected to symmetric rolling instead (Figure 7). The reason for the increase is the forming of ultrafine-grained microstructure as a result of the refinement taking place because of the shearing stresses acting on the sheets [11].

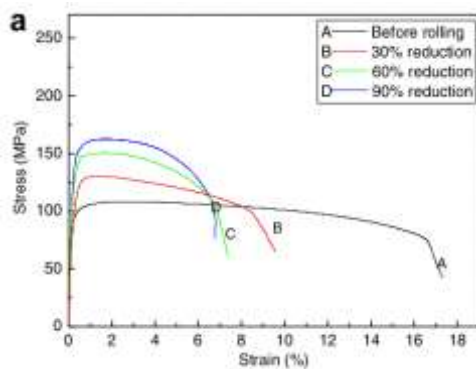


Figure 6: Stress-Strain diagram of an aluminium specimen undergoing symmetric rolling [11]

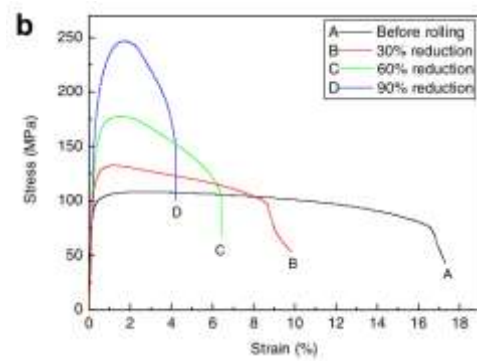


Figure 7: Stress-Strain diagram of an aluminium specimen undergoing asymmetric rolling [11]

A similar experiment was conducted using blanks made of magnesium alloy. The cross-section is reduced by 25% during both the symmetric and asymmetric methods of rolling. In the results shown in Figure 8, the tensile strength, yield strength and the deformation the material is capable of sustaining before failure are increased [12].

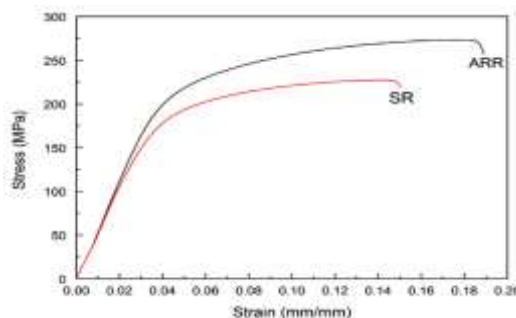


Figure 8: Stress-Strain diagram of blanks made of AZ31, undergoing symmetric (SR) and asymmetric (ARR) rolling [12]

From a technological point of view, AR is easy to implement because of the possibility to most easily alter the symmetric rolling process by changing the smallest number of parameters. Despite the conceptual and experimental proof of the increase in mechanical properties of the material, the process is considered to be unstable because of the phenomenon of roller slipping which is examined during AR [13].

Cryorolling (CR)

Another modification of the existing conventional method, shown on Figure 9, this type of rolling is taking place in conditions that permit reaching of cryogenic temperature [14]. The process consists of initial submerging of the material in a container full of cooling liquid, most often that being liquid nitrogen, and afterwards subjecting it to symmetric rolling. After the blank is rolled, it is submerged into the container again. As a result, the natural recovery processes in the material are suppressed, which leads to the refinement of its microstructure thus increasing its strength and plasticity.

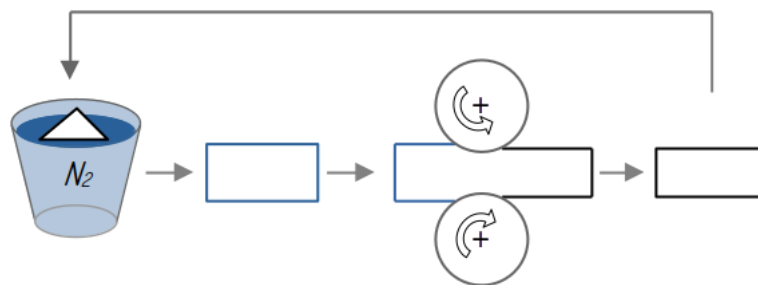


Figure 9: A simplified depiction of the cryorolling technological process

The physical and mechanical properties of cryorolled samples are subjected to testing, as shown in Figure 10. In it, the stress-strain diagram of samples rolled alongside the grain and across it both in room temperature and in cryogenic conditions is shown. The values lead to the conclusion that compared to materials subjected to conventional rolling, their cryorolled counterparts exhibit increased yield strength and ultimate tensile strength as improvement of up to 30% is possible [15].

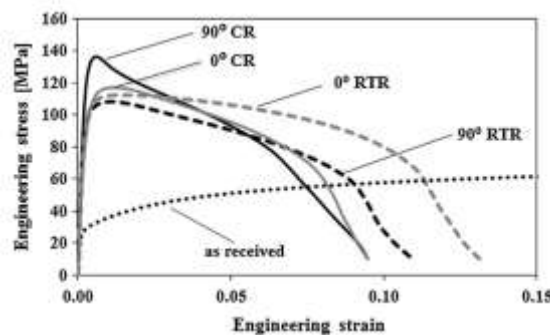


Figure 10: Stress-Strain diagram of blanks made of 99.6% aluminium, rolled alongside the grain and perpendicularly across the grain both in room temperature (RTR) and cryogenic temperature (CR) [15]

Being conceptually simple to adapt and in combination with the relatively high increase in mechanical properties of the sheet metals produced by it, make cryorolling a compelling method to be further researched. Considerations on if and how containers of liquid nitrogen can be implemented and stored in manufacturing sites remains a factor.

Accumulated Roll-Bonding (ARB) and Cross-Accumulated Roll Bonding (CARB)

One of the earliest methods for fabrication of UFG materials, the accumulated roll-bonding (ARB), shown on Figure 11, uses unmodified rolling mills. The metal sheets are prepared by its surfaces being subjected to abrasive wear and are afterwards stacked on top of each other before being fed into the rolls. The rolling process conjoins them together, halving their cross-section in half. The new sheet is then cut into two pieces ready to have the whole sequence of operations performed again as many times as it is deemed necessary.

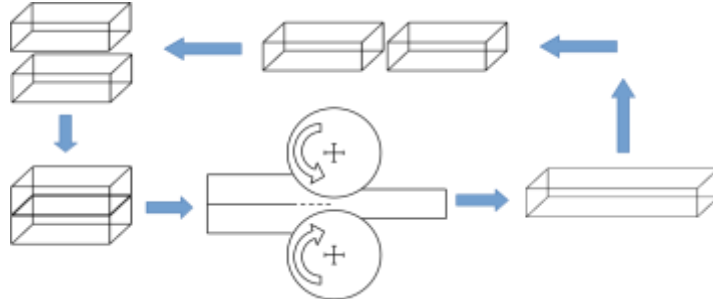


Figure 11: A simplified depiction of the accumulated roll-bonding technological process (ARB)

Despite the theoretical and practical possibility for endless iterations of the ARB process on a single sheet of paper, from a rational point of view, it is applicable with the most distinctive results in terms of change in its physical and mechanical properties only a few times because of diminishing returns. On Figure 12 are shown the results of an experiment conducted by R. Radev [16], where a piece of sheet metal alloy AA 1050 is subjected to 8 ARB passes and the values of the hardness of the alloy and its grain size have been recorded. The numbers show a tendency to reach a plateau-like trajectory starting from the 6-th pass onward. A similar experiment is carried out by measuring the tensile strength and the elongation of the material [17], as interpretation of the values leads to a similar conclusion.

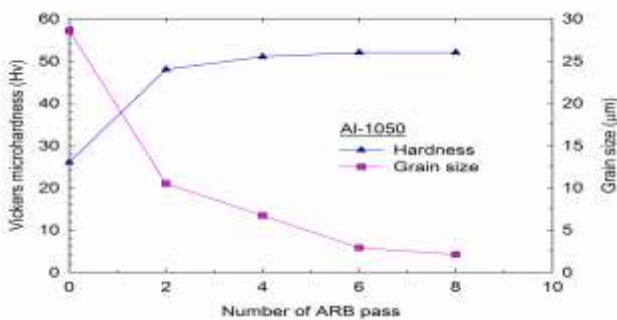


Figure 12: Dependency between the ARB passes, the hardness of the material and the grain size of aluminium alloy AA 1050 [16]

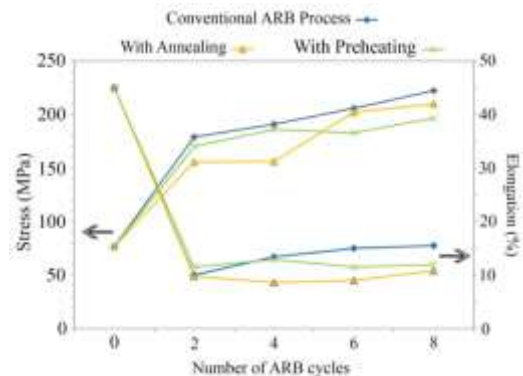


Figure 13: Dependency between the ARB passes, the tensile strength and the elongation of aluminium alloy AA 1050 [17]

ARB also creates a premise for the occurrence of plastic anisotropy in the material, which is due to the multiple rolling in the same direction, which further elongates the grains. This is visible on Figure 14, depicting pictures taken by microscope, showing the longitudinal cross-section of a steel strip that has undergone multiple ARB passes and the respective grain elongation after the operations [18].

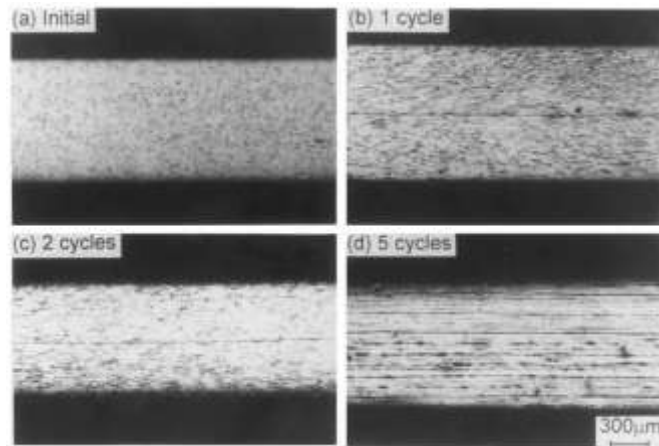


Figure 14: Longitudinal cross-section of a steel strip subjected to ARB and examined under microscope [18]

In order to reduce plastic anisotropy, a small change in this method is introduced. Displayed on Figure 15 is the principal scheme of the cross-accumulated roll bonding (CARB) process, which does not differ from ARB except from the added rotation of the sheets by 90 degrees before them being fed between the rolls. This way every next rolling operation will be carried out perpendicularly to the direction of the previous one [19].

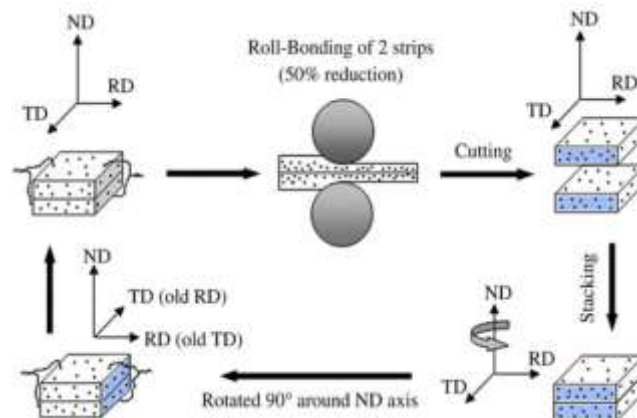


Figure 15: A simplified depiction of the cross-accumulated roll-bonding (CARB) [19]

It is experimentally proven that sheets subjected to CARB possess greater yield and tensile strength and hardness compared to those under ARB in both aluminium composites [20], and aluminium alloys [21].

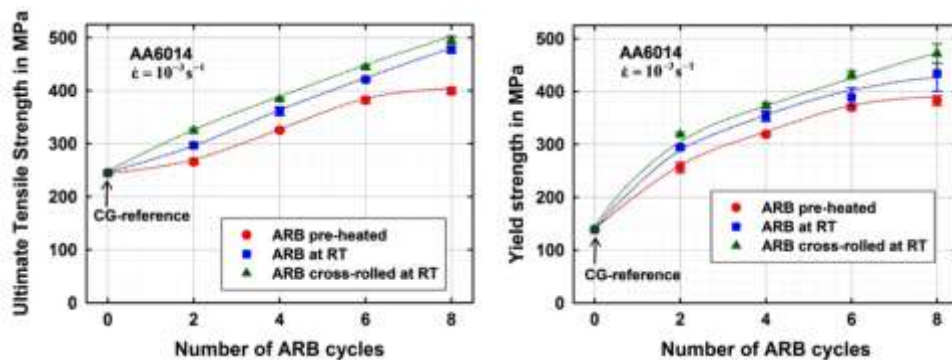


Figure 16: Dependency between the tensile strength of sheets of alloy AA 6014, subjected to ARB and CARB, and the number of passes [21]

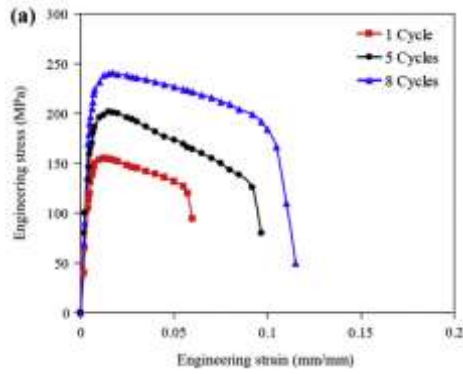


Figure 17: Dependency between the tensile strength of sheets of composite $Al-Al_2O_3$, subjected to ARB and its ductility [20]

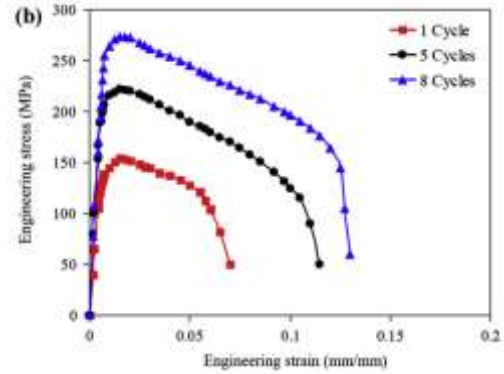


Figure 18: Dependency between the tensile strength of sheets of composite $Al-Al_2O_3$, subjected to CARB and its ductility [20]

Even though the sheets made by CARB have increased physical and mechanical properties, their production on manufacturing scale is more difficult from a technological point of view due to the method's requirement of sheet rotation. This condition can grow into a more serious problem with the increase in size of the blanks.

Repeated Corrugation and Straightening via Rolling (RCSR)

Shown on Figure 19, in this method, the sheet is fed between rolls with non-cylindrical shapes, thus deforming the sheet in a wavy pattern and creating shearing, compression and tensile stresses in different areas of it as a result. After passing through that set of rolls, the sheet is fed into another set of cylindrical rolls, which straighten its shape. Afterwards, the specimen is either flipped by 180° and the steps are repeated, or it is fed into rolls with a mirrored shape, aiming to subject the areas of the sheet previously under compression stress to tension and vice-versa [22].

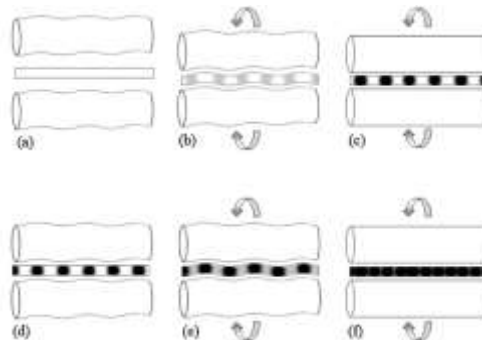


Figure 19: Principle of operation of the RCSR process [22]

Of all aforementioned severe plastic deformation techniques, this one is the most applicable for producing large metal sheets because of the simplicity of the rolling mills and the capability for implementation in large manufacturing sites [4], but a serious disadvantage is the less homogeneous structure of the material and its failure likelihood because of its subsection to both compression and tension at the same time.

CONCLUSION

In this article have been described a small number of methods for fabrication of ultrafine-grained structured materials, focusing on the most recent and the most established techniques for sheet metal production. Despite their implementation on a manufacturing scale not being possible at this point, because of the practical considerations that those methods require, progress has been made

in terms of the conceptual ideas and the conducted experiments, which are promising enough to be further researched on the possibility to remove or mitigate their disadvantages.

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