Journal of Metallic Materials 2021, 73 (3), p. 7–22

DOI: 10.32730/imz.2657-747.21.3.2

Jerzy STĘPIEŃ, Marek BURDEK, Jarosław MARCISZ, Artur ŻAK

Łukasiewicz Research Network – Institute for Ferrous Metallurgy
Sieć Badawcza Łukasiewicz – Instytut Metalurgii Żelaza

Jacek JANISZEWSKI

Military University of Technology, Faculty of Mechatronics, Armament and Aerospace
Wojskowa Akademia Techniczna, Wydział Mechatroniki Uzbrojenia i Lotnictwa

MICROSTRUCTURE, MECHANICAL PROPERTIES AND GEOMETRY OF A MODEL BATCH OF SEMI-SPHERICAL STEEL LINERS INTENDED FOR USE IN THE EXTRACTIVE INDUSTRY

MIKROSTRUKTURA, WŁAŚCIWOŚCI MECHANICZNIE I GEOMETRIA PARTII MODELOWEJ STALOWYCH WKŁADEK KUMULACYJNYCH PÓŁSFERYCZNYCH PRZEZNACZONYCH DO ZASTOSOWANIA W PRZEMYŚLE WYDOBYWCZYM

The article presents the results of investigation of the microstructure and mechanical properties of Fe-based materials intended for the production of semi-spherical liners for experimental shaped charges. The tests were carried out on samples taken in three directions in relation to the rolling direction: 0°, 45° and 90°, of the following materials: cold-rolled sheets made of DC04 steel, hot-rolled sheets made of 04J steel, and cold-rolled strips made of 004G steel developed at Łukasiewicz – IMŻ and annealed at 650°C. Semi-spherical drawpieces with a diameter of 106.4 mm, intended for liners, were made of the sheets with the use of cold stamping. Tests of the microstructure and HV hardness of samples taken from the test batch were carried out on cross-sections along the pressing direction and the model batch – on sections transverse to the stamping direction The geometry of the model batch drawpieces was also measured. The ferrite grain size evaluation was performed according to the ASTM E112 standard using µgrain software with a grain size evaluation module using counting the number of intersections of grain boundaries with a circle.

Keywords: *shaped charge liner, drawpiece, steel sheet, microstructure, mechanical properties, mean chord, ferrite grain size distribution*

Przedstawiono wyniki badań mikrostruktury i właściwości mechanicznych materiałów na bazie Fe przeznaczonych do wytwarzania wkładek półsferycznych do eksperymentalnych ładunków kumulacyjnych. Badania wykonano na próbkach pobranych w trzech kierunkach w stosunku do kierunku walcowania 0°, 45° i 90° z następujących materiałów: blach walcowanych na zimno ze stali DC04, blachy walcowanej na gorąco ze stali 04J oraz taśm walcowanych na zimno i wyżarzanych w temperaturze 650°C ze stali 004G opracowanej w Łukasiewicz – IMŻ. Z blach metodą tłoczenia na zimno wykonano wytłoczki półsferyczne o średnicy 106,4 mm przeznaczone na wkładki kumulacyjne. Przeprowadzono badania mikrostruktury i twardości HV próbek pobranych z partii testowej na przekrojach wzdłuż kierunku tłoczenia i partii modelowej – na przekrojach poprzecznych do kierunku tłoczenia oraz pomiary geometrii wytłoczek partii modelowej. Badania wielkości ziaren ferrytu wykonano zgodnie z normą ASTM E112 z zastosowaniem oprogramowania µgrain z modułem do oceny wielkości ziarna metodą zliczania liczby przecięć granic ziaren z okręgiem.

Słowa kluczowe: *wkładka kumulacyjna, wytłoczka, blacha stalowa, mikrostruktura, właściwości mechaniczne, średnia cięciwa, rozkład wielkości ziaren ferrytu*

1. INTRODUCTION

A symmetrical cavity in the explosive charge (charge cavity) causes the effect of concentration of the explosion energy. The effect of the directional action of the cavity charge can be increased by lining the cavity with a layer of a solid body in the shape of the cavity [1, 2]. The layer is called the liner. As a result of detonation of the explosive, the liner is deformed, causing the internal surface to move towards the geometric centre of the liner. The liner closes, and it is extremely important that the liner closes symmetrically to its axis and that the material has isotropic properties. In the process of closing the liner, a jet of high velocity is generated, which consists of particles torn from the inner surface of the material and air. This jet is called the cumulative jet and is characterised by high kinetic energy of particles at a significant temperature of approx. 400–600°C.

The formation of the jet ends when the liner closes under the influence of the pressure of blast gases as a result of a significant erosion of the material of the inner wall and

Corresponding Author: Jerzy Stępień, email: jerzy.stepien@imz.lukasiewicz.gov.pl
Sieć Badawcza Łukasiewicz – Instytut Metalurgii Żelaza, ul. K. Miarki 12-14, 44-100 Gliwice, Poland

as a result of a significant thinning of the walls of the liner. The kinetic energy of this form of liner is low. The mass of the cumulative jet generated from the conical liner is up to 30% of the liner mass, and the jet front reaches the velocity in the range of 7–10 km/s [1]. The parameters of the jet depend on many factors, which include, first of all, the shape of the liner, shape of the explosive charge, method of initiating the explosive, etc., and the type of the explosive. The quality of the liner material, as well as the accuracy of the liner, i.e. its geometric correctness, also have a significant impact on the penetration efficiency of the cumulative jet [3, 4]. On the basis of the research and analyses carried out so far, it was found that a material with a single-phase structure, characterised by good ductility, is advantageous [3, 4]. In particular, a significant requirement for materials intended for liners is high ductility in conditions of dynamic strain occurring at a rate of approx. 10,000 s^{-1}.

The explosive with the liner and the cover form a shaped charge. Shaped charges are used in the defence, extractive or geology industries and are still the subject of works and analyses by many world research centres [5–10]. Research is being carried out to define the characteristics of the material, important in terms of the penetrating capacity of the cumulative jet. Specially designed shaped charges are used, for example, for perforation of geological or production wells [7–9].

An important parameter determining the value of the energy transferred to the obstacle by the cumulative jet and, consequently, the depth of its penetration is the distance of the charge from the obstacle. In practice, a distance of 1 to 3 calibre of the liner is often used, but it does not always ensure obtaining the maximum depth of the hole [10]. The environment in which a given shaped charge is to be used is not without significance. The analysis of the possibility of using shaped charges in drilling holes in the extractive industry is presented in literature [11]. It was found that the use of shaped charges equipped with liners made of a material with the desired physico-mechanical properties can increase the efficiency of drilling in terms of the diameter and depth of the penetration hole.

The article presents the results of research carried out under the project "Materiały o strukturze nanokrystalicznej i amorficznej do konstrukcji wkładek kumulacyjnych do zastosowania w przemyśle wydobywczym [Materials with a nanocrystalline and amorphous structure for the construction of shaped charge liners for use in the extractive industry]" (TECHMATSTRATEG) [13–17]. The study concerned iron-based alloys intended for the production of semispherical liners with a diameter of 106.4 mm dedicated for loads applicable in the extractive industry. The project was carried out by a consortium consisting of five research units: Łukasiewicz – Institute of Non-Ferrous Metals – Project Leader, Łukasiewicz – Institute for Ferrous Metallurgy, GiG Research Institute, Military University of Technology, Military Institute of Armament Technology, and an entrepreneur – Chemical Works NITRO-CHEM S.A. The main goal of the project is to develop a series of shaped charges of various calibres for use in the extractive industry for drilling holes or crushing rocks. As part of the project in the field of explosive construction, it is planned to use liners made of alloys based on Fe and Cu. The studies carried out at Łukasiewicz – IMŻ concerned the selection of the material of the liners and the development of the technology for their production on a mass scale, along with the production of a model batch of Fe-alloy liners. Based on the available literature data and on the basis of the research experience of the consortium members, it was assumed that the material for the production of drawpieces for the liners should have a homogeneous microstructure. It was assumed that a material with a single-phase microstructure, high purity and good plasticity would have favourable properties from the point of view of the effectiveness of the charge operation.

The project proposed the use of semispherical liners with a diameter of 106.4 mm, made of high-purity iron-based Fe-Armco alloys and DC04 deep-drawn steel. Cold-rolled (DC04) and hot-rolled (04J) sheets were prepared for the target production technology of liners using stamping. Steel semi-spherical liners with a diameter of 106.4 mm are made of a material selected by Łukasiewicz – IMŻ in the form of discs with a diameter of 165 mm and a thickness of 2.5 mm.

The scope of work carried out at Łukasiewicz – IMŻ included studies on the size and distribution of ferrite grains in steel, mechanical properties of the used materials and geometry of the model batch with a diameter of 106.4 mm. Based on the effectiveness of the estimated crater drilling depth in model samples, the geometry and technology of shaping semispherical liners made of Fe-alloy material were developed.

2. MATERIAL, SCOPE AND METHODOLOGY

The tests were carried out on three types of materials for liners made of Fe-based alloys with a diameter of 106.4 mm of the test batch of shaped charges, i.e. cold-rolled DC04 steel sheets, hot-rolled 04J sheets and cold-rolled strips made of experimental steel (designated as 004G) developed at Łukasiewicz – IMŻ in semi-industrial conditions of the line for process simulation (LPS). The ingots from the experimental 004G steel were smelted and cast in a vacuum furnace, thus ensuring high metallurgical purity of the steel, and then the strips were hot rolled in the LPS semi-industrial line to a thickness of approx. 3.5 mm and a width of approx. 175 mm, and finally the strips were etched for cold rolling, which was done under industrial conditions at Walcownia Metali Nieżelaznych "Łabędy" in Gliwice. As a result of cold rolling in two passes, strips with a thickness of 2.45 to 2.60 mm were obtained. The sheets and strips were subjected to heat treatment of homogenisation annealing at 650°C, from which discs with a diameter of 165 mm were cut out. The material varied in terms of the content of C and Mn. The chemical composition of the steels intended for liners with a diameter of 106.4 mm is presented in Table 1.

Table 1. Chemical composition of materials used for examination

Tabela 1. Skład chemiczny materiałów użytych do badań

Steel grade	C	Mn	Si	P	S	Al_{total}
DC4	0.08	0.40	–	0.03	0.03	–
04J	0.02	0.20	0.006	0.006	0.008	0.044
004G	0.005	0.41	0.010	0.006	0.006	0.008

The numerical sheet metal forming simulations show that the minimum load necessary to make a drawpiece in the shape of a ϕ106.4 mm semi-spherical liner made of 04J steel is approx. 1.4 MN [17, 18]. Taking into account the simulation results, it would be advisable to select a press with a nominal load of min. 1.8 MN with a tool stroke of approx. 150 mm, which would enable the correct stamping of the drawpiece.

The drawpieces for the production of the test batch liners were made on a PMS 160A press with a load of 1.6 MN and a stroke of 20–140 mm, i.e. with a slightly lower load and stroke than indicated by the simulation results.

Images of the drawpieces from the test batch of liners made of discs with a diameter of ϕ165 mm and thickness of 2.5 mm made of DC04 and 04J steel are shown in Fig. 1a (A1 – DC04 steel disc and B1 – 04J steel disc).

Using the selected technology, it was not possible to obtain drawpieces from 004G steel discs (Fig. 1b). The probable cause was a much worse surface quality of the disc and lower elongation (elongation: 12.8–14.8%) compared to discs made of DC04 and 04J steel (elongation: 35–44%).

The test batch liner drawpieces were cut along the main stamping axis (view in Fig. 2a) and samples were taken according to the diagram shown in Fig. 2b in order to study ferrite grain size distribution in the microstructure and to perform hardness measurement.

Based on the results of the tests of the test batch drawpieces in the process of producing the drawpieces, a correction was made consisting in increasing the final load of the press to the maximum, and in this way a model batch of DC04 and 04J steel drawpieces was made, examples of which are shown in Fig. 3. The study of the

Fig. 1. Photographs of correct liner drawpieces made of DC04 and 04J steel (a) and of defective drawpiece made of 004G steel (b)

Rys. 1. Fotografie prawidłowych wytłoczek wkładek kumulacyjnych ze stali DC04 i 04J (a) oraz wadliwej wytłoczki ze stali 004G (b)

Fig. 2. Liner drawpieces cut along the main stamping axis (a) and sampling diagram (b)

Rys. 2. Widok wytłoczek wkładek przeciętych wzdłuż głównej osi wytłaczania (a) i schemat pobierania próbek do badań (b)

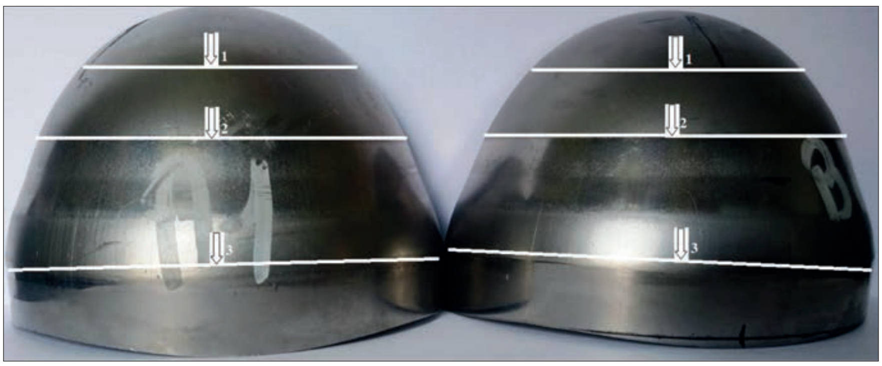

Fig. 3. Test sites for grain size and hardness measurement on the cross-section in relation to the main stamping axis of the model batch of liner drawpieces (A1 – steel DC04, B1 – steel 04J) 1 – bottom area, 2 – intermediate area, 3 – cap area

Rys. 3. Miejsca badań wielkości ziarna i twardości na przekroju poprzecznym w stosunku głównej osi wytłaczania partii modelowej wytłoczek wkładek kumulacyjnych (A1 – stal DC04, B1 – stal 04J) 1 – obszar dna, 2 – obszar pośredni, 3 – obszar kielicha

structure, hardness and evaluation of ferrite grain size in sections transverse to the main stamping axis on the wall thickness in three levels according to the diagram shown in Fig. 3 was performed on the model batches.

The scope of the material tests was as follows: stensile specimens were made of sheets and strips in three rolling directions: parallel 0°, perpendicular 90° and at an angle of 45° to the rolling direction. The tensile test determined yield strength, tensile strength and total elongation – $R_{p0.2}$, R_m and A_{80}. The structure, size and distribution of ferrite grains were examined in each of the three directions using a light microscope. The hardness was also measured.

The size of ferrite grain was assessed using the comparative method according to the standard scale included in the ASTM E112 [19] standard at the magnification up to 500× and with the use of μgrain software with a module for grain size evaluation using counting the number of grain intersections in a circle. The method of ferrite grain size evaluation using the circle counting method is presented in Fig. 4.

3. TEST RESULTS FOR SHEETS, STRIPS AND SEMI-SPHERICAL DRAWPIECES FROM SELECTED MATERIALS

3.1. RESULTS OF EXAMINATION OF MICROSTRUCTURE AND MECHANICAL PROPERTIES

The results of microstructure investigation in the examined materials are shown in Figs. 5-13 in three directions in order to determine its anisotropy.

Figs. 5–7 show the microstructure of cold-rolled sheets made of DC04 steel in the rolling direction: parallel (Fig. 5), at an angle of 45° (Fig. 6) and perpendicular (Fig. 7). The sheets are characterised by a ferritic structure with slightly elongated recrystallised grains, on sections parallel and perpendicular to the rolling direction.

Figs. 8–10 show the microstructure of hot-rolled sheets made of 04J steel, observed on samples taken in three directions in relation to the rolling direction: parallel (Fig. 8), at an angle of 45° (Fig. 9) and perpendicular (Fig. 10).

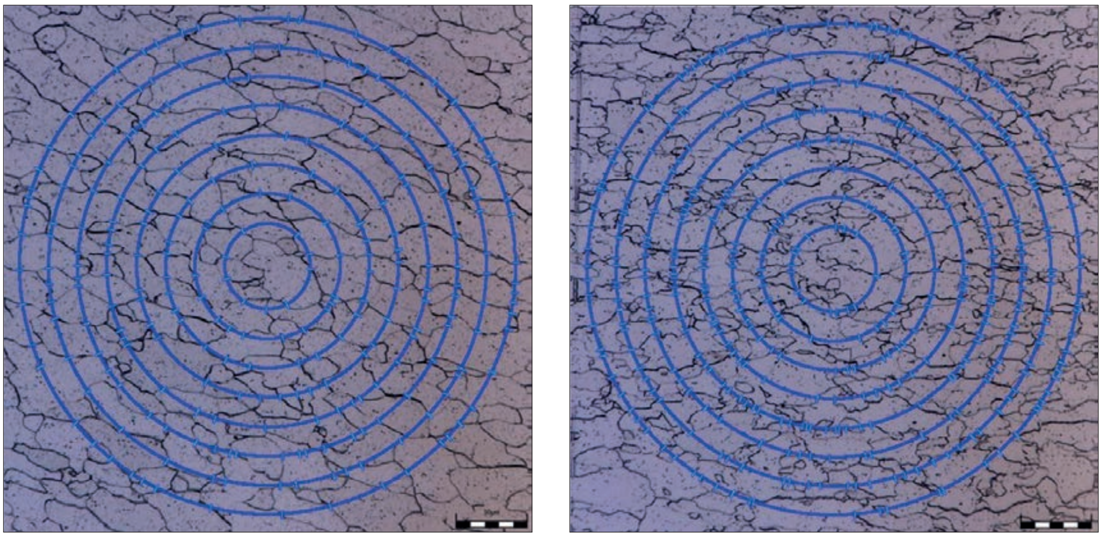

Fig. 4. Methodology of ferrite grain size measurement based on the guidelines of the ASTM E112 standard with the use of μgrain software. Examples of samples after stamping on the cross-section along the stamping axis: a) made of DC04 steel and b) made of 04J steel

Rys. 4. Metodyka pomiaru wielkości ziarna ferrytu w oparciu o wytyczne normy ASTM E112 z wykorzystaniem oprogramowania μgrain. Przykładowe próbki po wytłaczaniu na przekroju wzdłuż osi wytłaczania: a) ze stali DC04 i b) ze stali 04J

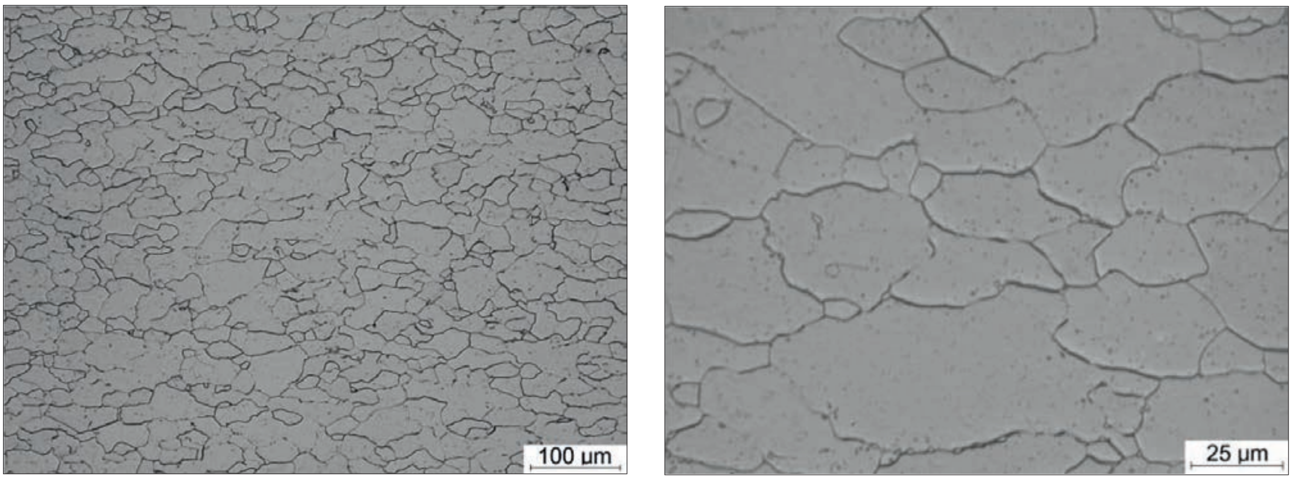

Fig. 5. Microstructure of DC04 steel sheets occurring in the direction perpendicular to the rolling direction, magn. 100× and 400×

Rys. 5. Mikrostruktura blach ze stali DC04 występująca w kierunku równoległym do kierunku walcowania, pow. 100× i 400×

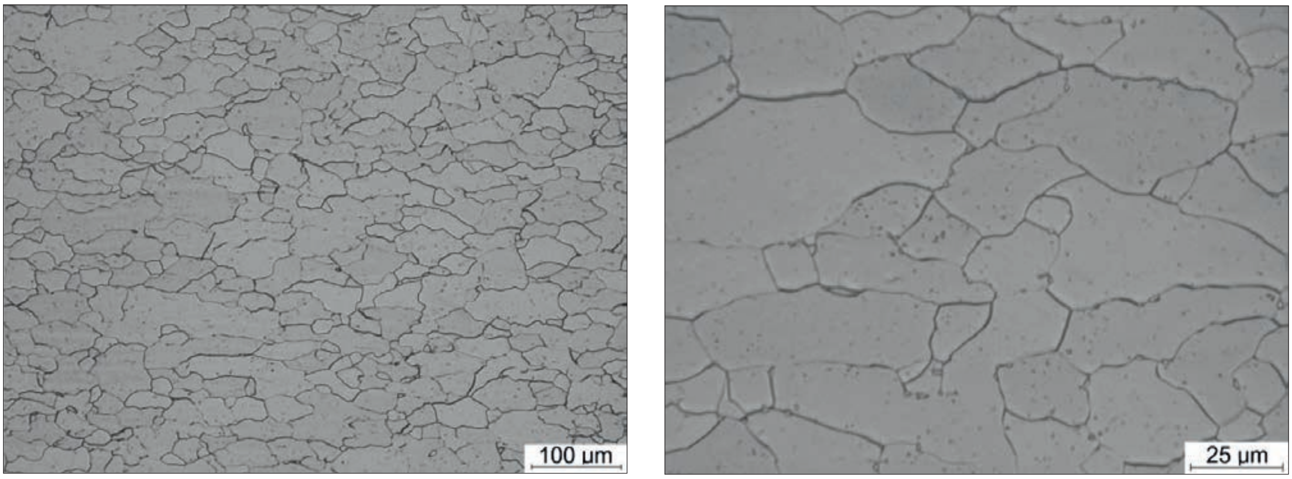

Fig. 6. Microstructure of DC04 steel sheets occurring in a 45° direction to the rolling direction, magn. 100× and 400×

Rys. 6. Mikrostruktura blach ze stali DC4 występująca w kierunku 45° do kierunku walcowania, pow. 100× i 400×

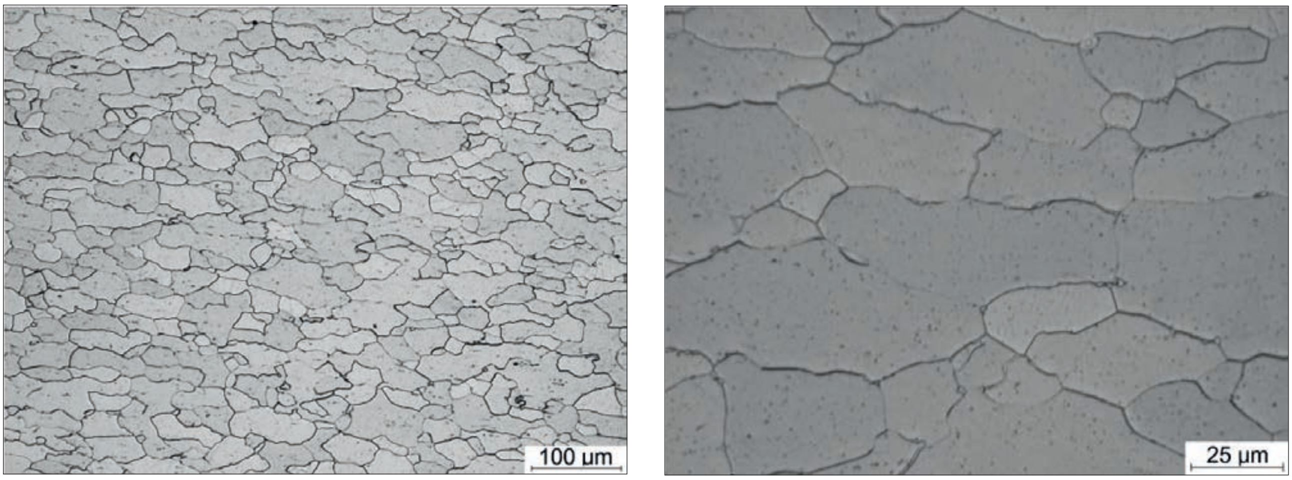

Fig. 7. Microstructure of DC04 steel sheets occurring in the direction transverse to the rolling direction, magn. 100× and 400×

Rys. 7. Mikrostruktura blach ze stali DC04 występująca w kierunku prostopadłym do kierunku walcowania, pow. 100× i 400×

Ferrite grains were characterised by irregular shapes of boundaries and a larger grain size range compared to DC04 steel. The grains had a shape that was slightly elongated in the rolling direction.

Figures 11–13 show the microstructure of 004G steel strips annealed at 65°C after cold rolling. The microstructure of the strips after cold rolling and annealing was observed in the following direction: parallel (Fig. 11), at an

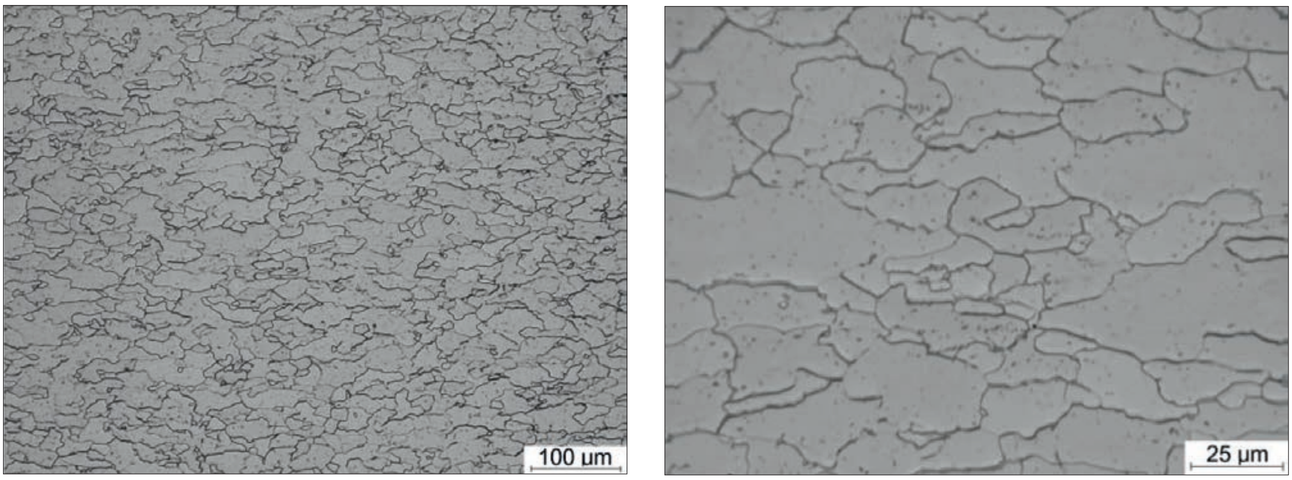

Fig. 8. Microstructure of 04J steel sheets occurring in the rolling direction, magn. 100× and 400×

Rys. 8. Mikrostruktura blach ze stali 04J występująca w kierunku zgodnym z kierunkiem walcowania, pow. 100× i 400×

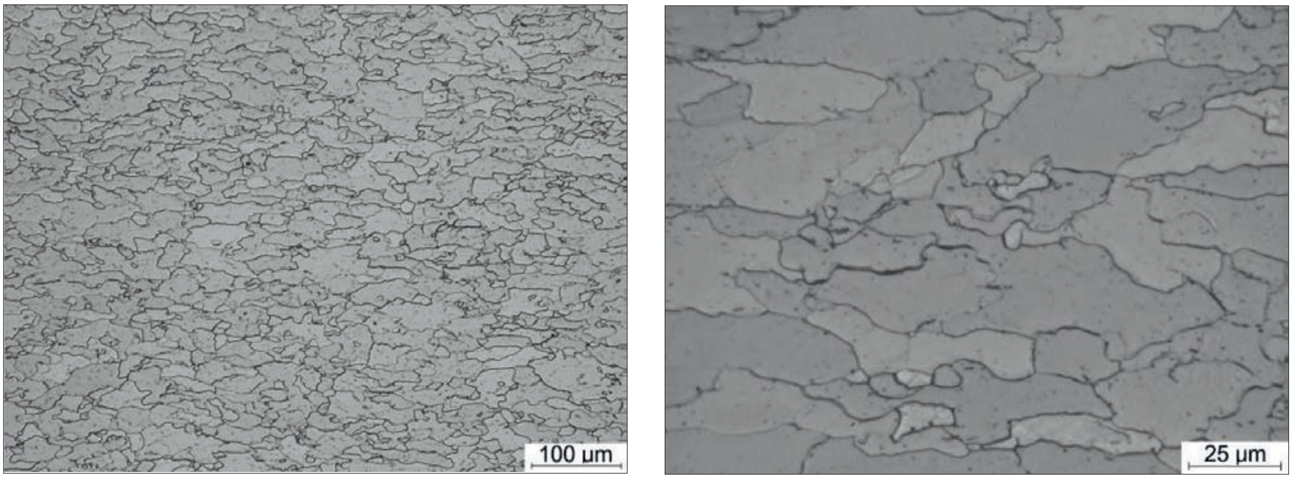

Fig. 9. Microstructure of 04J steel sheets occurring in a 45° direction to the rolling direction, magn. 100× and 400×

Rys. 9. Mikrostruktura blach ze stali 04J występująca w kierunku 45° do kierunku walcowania, pow. 100× i 400×

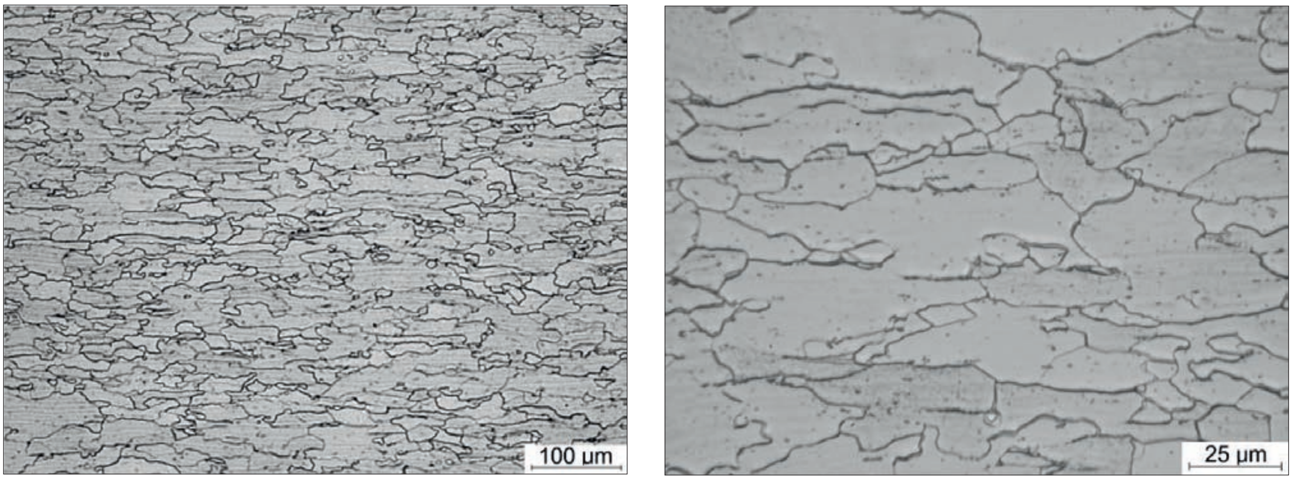

Fig. 10. Microstructure of 04J steel sheets occurring in the direction transverse to the rolling direction, magn. 100× and 400×

Rys. 10. Mikrostruktura blach ze stali 04J występująca w kierunku prostopadłym do kierunku walcowania

angle of 45° (Fig. 12) and perpendicular (Fig. 13) to the rolling direction.

Based on the structure images it was determined that in cold-rolled sheets made of DC04 steel, ferrite grains are larger, but more homogeneous in all three tested directions than in hot-rolled sheets of 04J steel and cold-rolled strips and those made of 004G steel after annealing at 650°C.

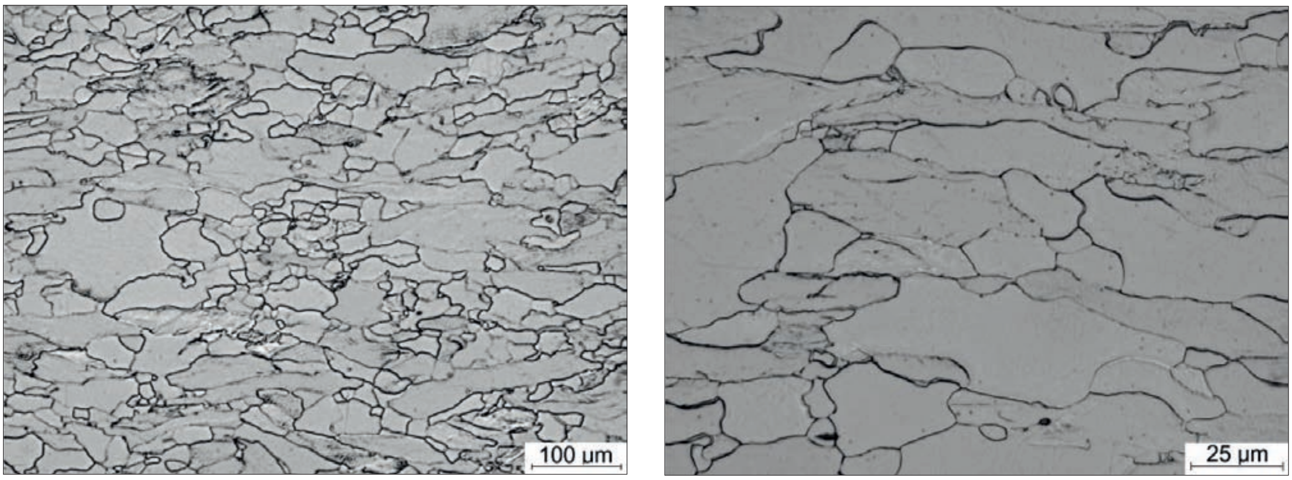

Fig. 11. Microstructure of 004G steel sheets after cold rolling and annealed at 650°C, occurring in the rolling direction, magn. 100× and 400×

Rys. 11. Mikrostruktura blach ze stali 004G po walcowaniu na zimno i wyżarzanych w temp. 650°C występująca w kierunku walcowania, pow. 100× i 400×

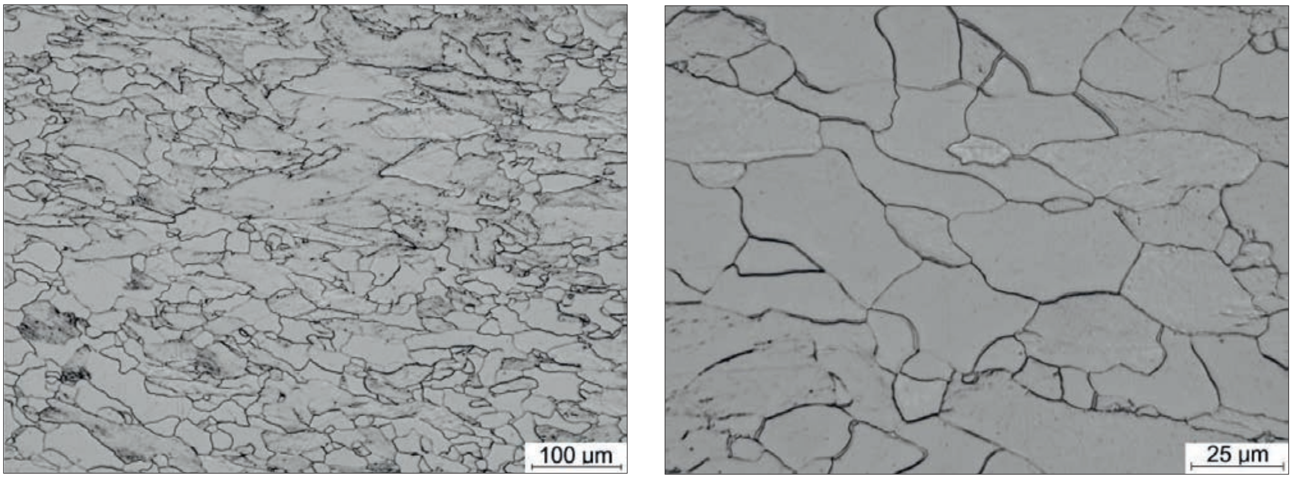

Fig. 12. Microstructure of 004G steel sheets after cold rolling and annealed at 650°C, occurring in the direction of 45° to the rolling direction, magn. 100× and 400×

Rys. 12. Mikrostruktura blach ze stali 004G po walcowaniu na zimno i wyżarzanych w temp. 650°C występująca w kierunku 45° do kierunku walcowania, pow. 100× i 400×

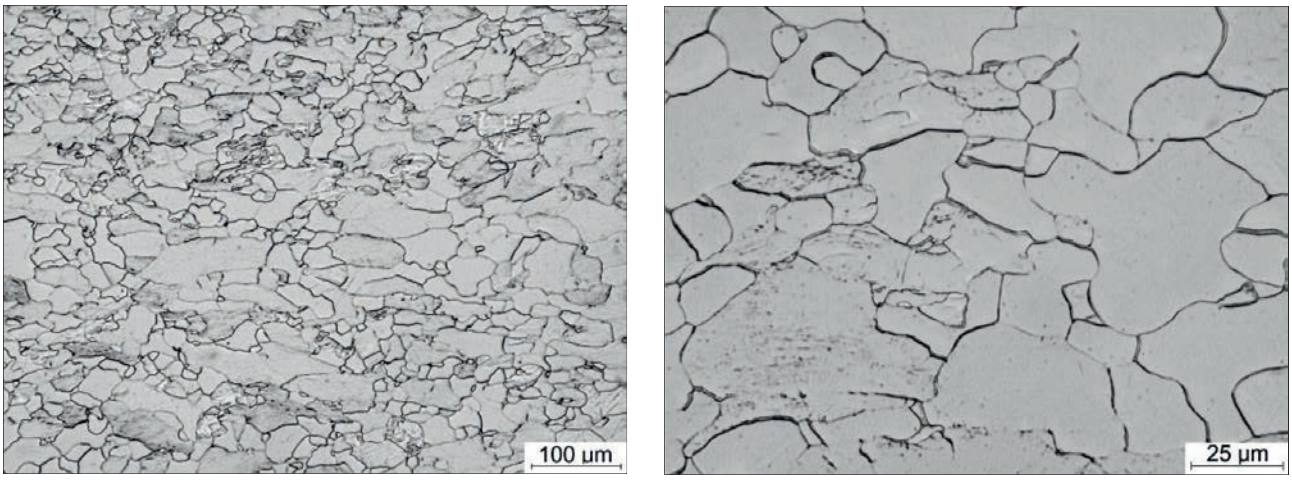

Fig. 13. Microstructure of 004G steel sheets after cold rolling and annealed at 650°C, occurring in the direction transverse to the rolling direction, magn. 100× and 400×

Rys. 13. Mikrostruktura blach ze stali 004G po walcowaniu na zimno i wyżarzanych w temp. 650°C występująca w kierunku prostopadłym do kierunku walcowania, pow. 100× i 400×

The mechanical properties in three directions: in the direction of rolling, at an angle of 45° to the rolling direction and perpendicular to the rolling direction, in DC4 and 04J sheets and in 004G steel strips are as follows:

- **in steel DC4**
  - 0° to the rolling direction they are
    $R_{p0.2}$ = 164 MPa; R_m = 291 MPa; A_{80} = 44.0%
  - 45° to the rolling direction they are
    $R_{p0.2}$ = 176 MPa; R_m = 303 MPa; $_{80}$ = 39.8%
  - 90° to the rolling direction they are
    $R_{p0.2}$ = 173 MPa; R_m = 290 MPa; A_{80} = 43.2%
- **in steel 04J (ARMCO)**
  - 0° to the rolling direction they are
    $R_{p0.2}$ = 202 MPa; R_m = 325 MPa; A_{80} = 39.6%
  - 45° to the rolling direction they are
    $R_{p0.2}$ = 226 MPa; R_m = 342 MPa; A_{80} = 34.7%
  - 90° to the rolling direction they are
    $R_{p0.2}$ = 220 MPa; R_m = 328 MPa; A_{80} = 36.0%
- **in steel 004G after annealing at 650°C:**
  - 0° to the rolling direction they are:
    $R_{p0.2}$ = 292 MPa; R_m = 346 MPa; A_{80} = 12.9%
  - 45° to the rolling direction they are:
    $R_{p0.2}$ = 264 MPa; R_m = 318 MPa; A_{80} = 14.8%
  - 90° to the rolling direction they are:
    $R_{p0.2}$ = 277 MPa; R_m = 333 MPa; A_{80} = 12.0%

The test results show that a greater anisotropy of mechanical properties is in 04J steel sheets and 004G steel strips than in DC4 steel sheets. A lower yield strength was found in sheets of steel DC04 (164-176 MPa) than in sheets of steel 04J (202–226 MPa) and 004G (264–284 MPa). On the other hand, sheets made of 004G steel were found to have a much lower elongation than sheets made of steels 04J and DC4. On average, in 004G steel sheets, A_{80} was approx. 13%, and in DC04 and 04J steel sheets it was approx. 40%.

The ferrite grain size evaluation was carried out in sheets made of DC04, 04J and 004G steel.

The summary of the results of the evaluation of ferrite grain size in DC04 and 04J steel sheets perpendicular to the rolling direction and in 004G steel strips after annealing at 650°C in three directions: parallel, at an angle of 45° and perpendicular to the rolling direction, is presented in Table 2.

Table 2. Summary of results of ferrite grain size evaluation in sheets and strips intended for liners

Tabela 2. Zestawienie wyników oceny wielkości ziarna ferrytu w blachach i taśmach przeznaczonych na wkładki kumulacyjne

Material		Average chord [μm]	Grain No. G per ASTM E112
DC04 cold-rolled sheet	Near the upper edge	22.16	7.7
	In the sheet's centre	19.49	8
	Near the lower edge	21.63	7.7
	Average	**21.01**	**7.8**
04J hot-rolled sheet	Near the upper edge	13.45	9.1
	In the sheet's centre	12.74	9.3
	Near the lower edge	12.87	9.2
	Average	**13.01**	**9.2**
004G cold-rolled strip	Ann. 650°C/dir. 0°	12.32	8.9
	Ann. 650°C/dir. 45°	13.99	9.1
	Ann. 650°C/dir. 90°	13.63	9.1
	Average	**13.31**	**9.1**

The presented evaluation of ferrite grain size, carried out in accordance with the guidelines of the ATSM E112 standard, shows that the average chord in DC04 steel sheets is approx. 21 μm, in 04J steel it is approx. 13 μm, and in strips made of 004G steel after annealing at 650°C it is approx. 13.3 μm.

3.2. IMAGE OF FERRITE GRAINS OF THE TEST BATCH OF DC04 AND 04J STEEL LINER DRAWPIECES REVEALED ALONG THE STAMPING DIRECTION

The image of ferrite grains revealed on the cross-sections along the stamping direction, taken according to the diagram presented in Fig. 2b, is shown in Fig. 14 (DC04 steel drawpieces – samples from A1 to A4) and in Fig. 15 (04J steel drawpieces – samples from B1 to B4).

Ferrite grains revealed on the longitudinal cross-sections of the DC04 steel liner after stamping (Fig. 14) are larger and with more regular border shapes than in the 04J steel drawpieces (Fig. 15). In the drawpieces made of both tested steels, ferrite grains are finer in the bottom area (A1 liner made of DC04 steel and B1 liner made of steel 04J) than in the cap area (A4 liner made of DC04 steel and B4 liner made of steel 04J).

The summary of the results of the evaluation of ferrite grain size in the drawpieces on the cross-sections along the stamping direction of the test batch liners made of DC04 and 04J steel is shown in Table 3, and in the form of grain size distribution histograms in Fig. 16 (DC04) and Fig. 17 (04J).

Table 3. Results of ferrite grain size evaluation in test batch drawpieces on sections along the stamping direction

Tabela 3. Wyniki oceny wielkości ziarna ferrytu w wytłoczkach partii testowej na przekrojach wzdłuż kierunku wytłaczania

Material		Average chord [μm]	Grain No. G per ASTM E112
DC04 cold-rolled sheet drawpieces	A1	20.20	8.0
	A2	21.04	7.8
	A3	23.02	7.6
	A4	23.09	7.6
	Average	**21.76**	**7.8**
04J hot-rolled sheet drawpieces	B1	12.77	9.3
	B2	12.50	9.4
	B3	13.74	9.1
	B4	13.11	9.2
	Average	**13.01**	**9.3**

The presented evaluation of ferrite grain size shows that the average chord in the drawpieces in the longitudinal section of the DC04 steel is over 21 μm, and in the drawpieces made of 04J steel is approx. 13 μm.

In the drawpieces made of DC04 and 04J steels, a similar change in grain size was obtained; the smallest ferrite grain occurs near the bottom of the drawpieces, and the largest ferrite grain occurs near the cap.

The results of HV1 hardness measurement of the drawpieces made of DC04 steel (samples A1 – A4) and steel 04J (samples B1 – B4) are presented in Table 4. Measurements 1 to 5 were taken in the centre of the wall thickness of the drawpiece measured from the cap side towards the bottom of the drawpiece. Measurement 6 was taken near the outer edge and measurement 7 was taken near the inner edge of the drawpiece's wall.

Table 4. Results of HV1 hardness measurement of the test batch of drawpieces for liners made of DC04 and 04J steel on cross-sections along the direction of stamping

Tabela 4. Wyniki pomiarów twardości HV1 partii testowej wytłoczek na wkładki kumulacyjne ze stali DC04 i 04J na przekrojach wzdłuż kierunku wytłaczania

Sample identification	HV 1 hardness measurement results							Mean value
	Imprints from cap toward bottom					OTR edge	INR edge	
	1	2	3	4	5	6	7	
A1	127	128	125	129	128	133	121	127.3
A2	124	116	123	125	120	128	125	123.0
A3	137	145	138	142	149	139	147	142.4
A4	144	159	155	167	161	163	160	158.4
B1	142	145	144	139	147	151	137	143.6
B2	143	139	136	132	142	143	137	138.0
B3	161	165	160	162	159	156	162	160.7
B4	182	180	180	183	173	180	171	178.4

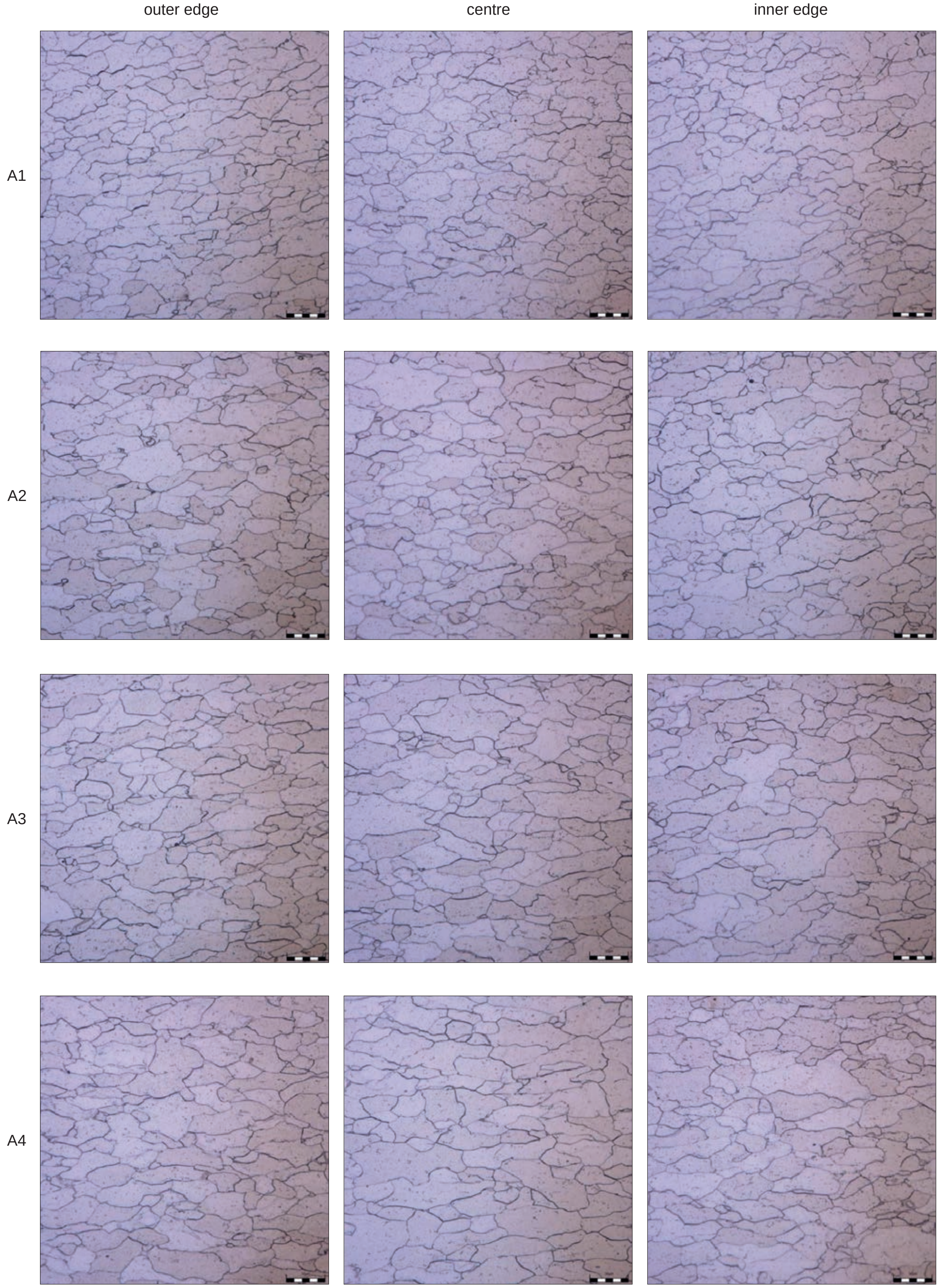

Fig. 14. Ferritic structure in the drawpiece of the DC04 steel test batch liner in the bottom area (sample A1), in the arc area between the bottom and the side surface (sample A2), in the side surface area (sample A3) and in the cap area (sample A4), as indicated in Fig. 2b; magn. 750×

Rys. 14. Struktura ferrytyczna występująca w wytłoczce wkładki kumulacyjnej partii testowej ze stali DC04 w obszarze dna (próbka A1), w obszarze łuku pomiędzy dnem a pobocznicą (próbka A2), w obszarze pobocznicy (próbka A3) i w obszarze kielicha (próbka A4), jak zaznaczono na rys. 2b; pow. 750×

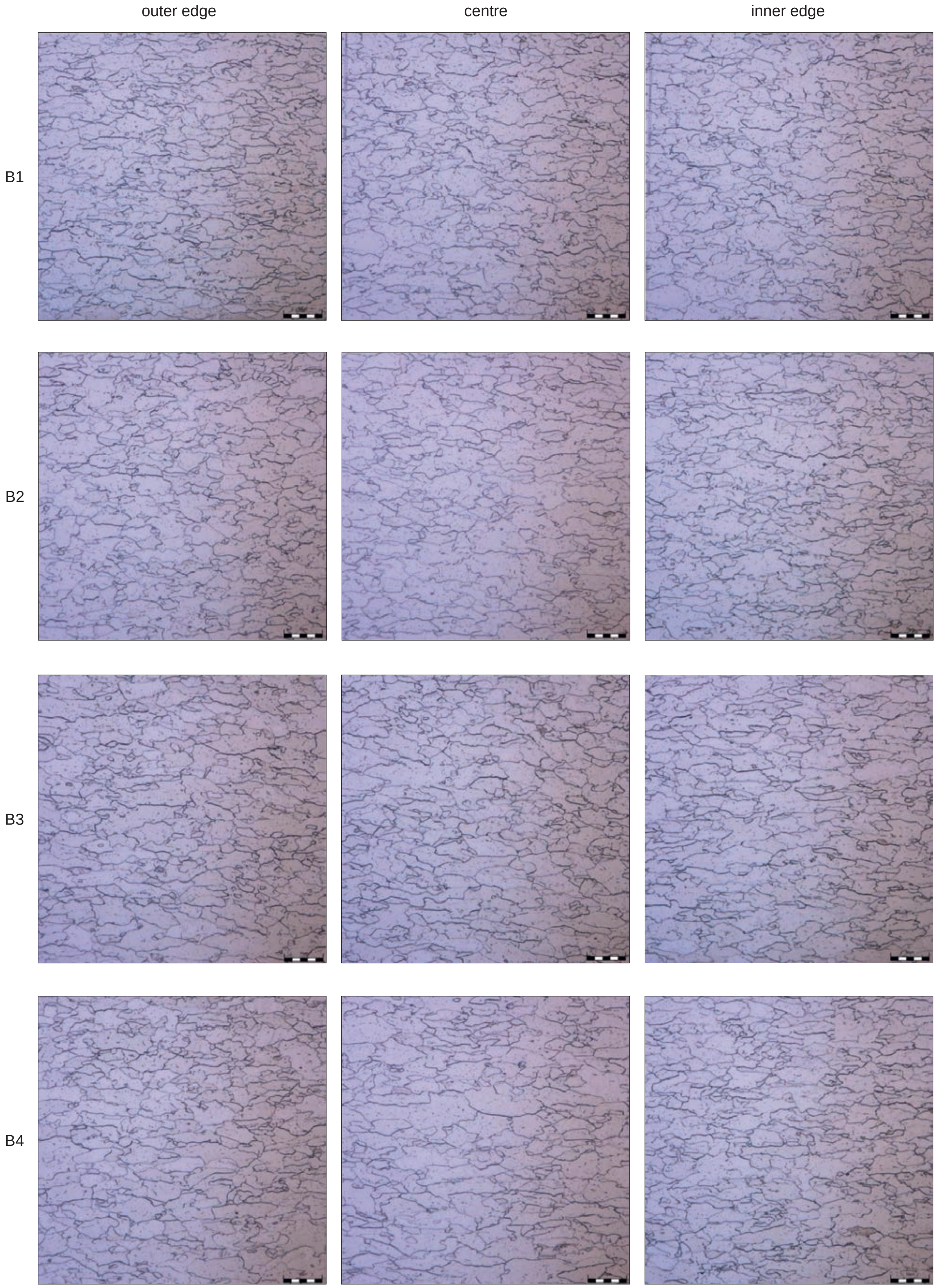

Fig. 15. Ferritic structure present in the drawpiece of the 04J steel test batch liner in the bottom area (sample B1), in the arc area between the bottom and the side surface (sample B2), in the side surface area (sample B3) and in the cap area (sample B4), as indicated in Fig. 2b; magn. 750×

Rys. 15. Struktura ferrytyczna występująca w wytłoczce wkładki kumulacyjnej partii testowej ze stali 04J w obszarze dna (próbka B1), w obszarze łuku pomiędzy dnem a pobocznicą (próbka B2), w obszarze pobocznicy (próbka B3) i w obszarze kielicha (próbka B4), jak zaznaczono na rys. 2b; pow. 750×

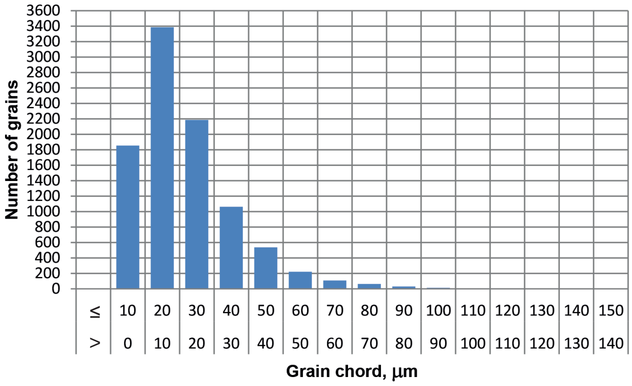

Fig. 16. Histogram of ferrite grain size distribution in drawpieces of the test batch made of DC04 steel revealed in the direction of stamping

Rys. 16. Histogram rozkładu wielkości ziaren ferrytu występujących w wytłoczkach partii testowej ze stali DC04 ujawnionych w kierunku wytłaczania

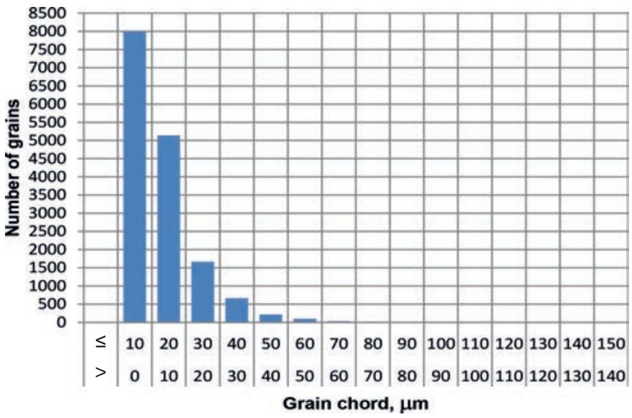

Fig. 17. Histogram of ferrite grain size distribution in drawpieces of the test batch made of 04J steel revealed in the direction of stamping

Rys. 17. Histogram rozkładu wielkości ziaren ferrytu występujących w wytłoczkach partii testowej ze stali 04J ujawnionych w kierunku wytłaczania

The hardness of DC04 and 04J steel drawpieces after stamping in the area of the bottom and the cap is different. In both cases, the hardness of the bottom area is lower than that of the cap area. For DC04 steel drawpieces it is 127.3 HV1 (bottom area) and 158.4 HV1 (cap area), and for 04J steel drawpieces it is 143.6 HV1 and 178.4 HV1. After stamping, the hardness of the DC04 steel drawpiece is lower than that of the 04J steel drawpiece with respect to individual areas of the drawpieces.

3.3. IMAGE OF FERRITE GRAIN IN THE MODEL BATCH OF DC04 AND 04J STEEL LINER DRAWPIECES REVEALED TRANSVERSE TO THE STAMPING DIRECTION

Ferrite grains were revealed at three levels of model batch drawpieces (diagram in Fig. 3) in the bottom area (level 1), in the intermediate area (level 2) and in the cap area (level 3). The bottom area and the intermediate area determine the formation of the cumulative jet, and the cap area forms the counter-jet.

The image of ferrite grains revealed on the cross-sections of the DC04 steel drawpieces is shown in Fig. 18, and of steel 04J – in Fig. 19.

The ferrite grains revealed on the transverse cross-sections of the DC04 steel model batch drawpieces after stamping (Fig. 18) are larger and with more regular border shapes than in the 04J steel drawpieces (Fig. 19).

A comparison of the results of ferrite grain size evaluation with grain software including a µgrain size evaluation module using the method of counting the number of grain intersections in a circle based on the ASTM E112 guidelines occurring in DC04 and 04J steel drawpieces of the model batch at the cap and bottom level in the direction perpendicular to the direction of the stamping axis is shown in Table 5, and in the form of grain size distribution histograms – in Figs. 20–23.

Table 5. Summary of the results of the evaluation of ferrite grain size in drawpieces at the cap and bottom level in sections transverse to the model batch stamping direction

Tabela 5. Zestawienie wyników oceny wielkości ziaren ferrytu w wytłoczkach na poziomie kielicha i dna w przekrojach poprzecznych do kierunku wytłaczania partii modelowej

Material		Average chord [µm]	Grain No. G per ASTM E112
DC04 liner drawpieces	Cap area	17.49	8.4
	Bottom area	18.93	8.1
04J liner drawpieces	Cap area	11.87	9.5
	Bottom area	11.67	9.5

1

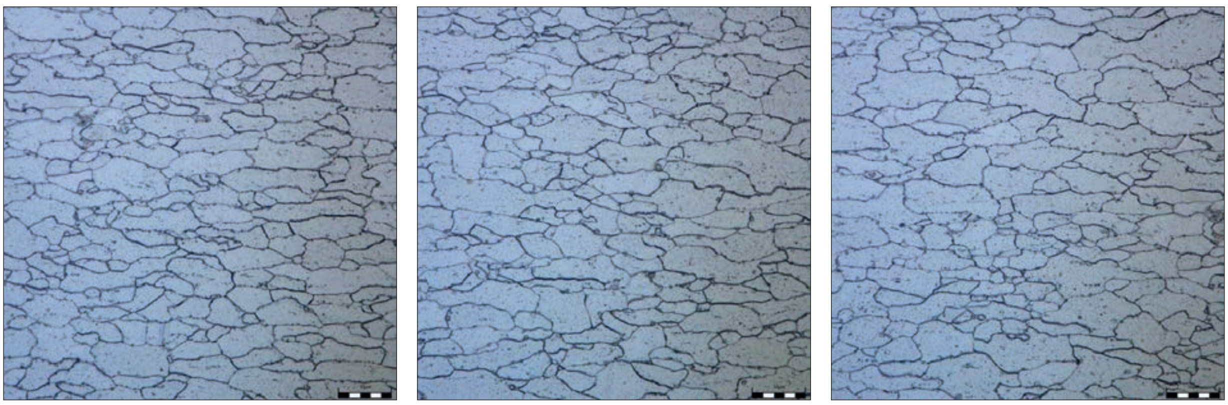

Fig. 18. Ferritic structure in the drawpiece of the DC04 steel model batch liner in the bottom area (level 1),as indicated in Fig. 3; magn. 750×

Rys. 18. Struktura ferrytyczna występująca w wytłoczce wkładki kumulacyjnej partii modelowej ze stali DC04 w obszarze dna (poziom 1), jak zaznaczono na rys. 3; pow. 750×

2

3

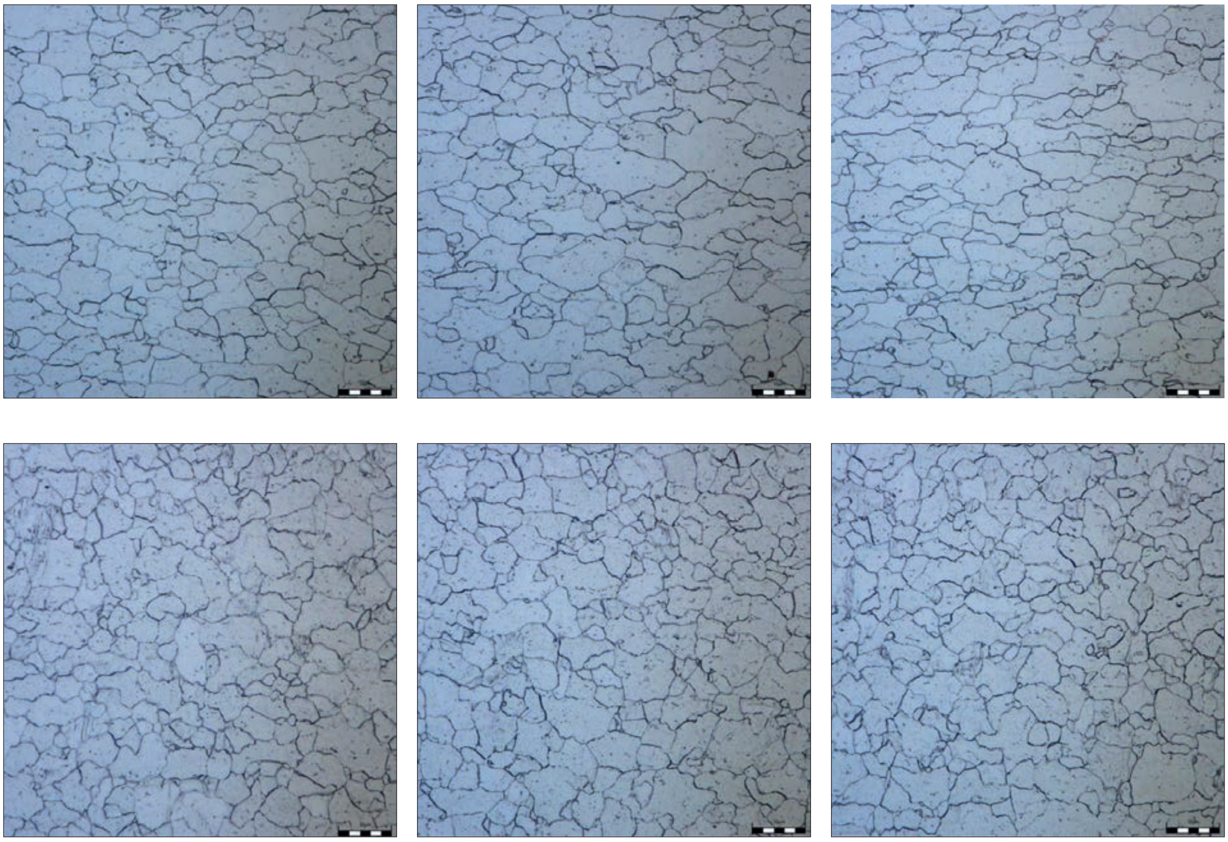

Fig. 18 cont. Ferritic structure in the drawpiece of the DC04 steel model batch liner in the side surface area (level 2) and in the cap area (level 3), as indicated in Fig. 3; magn. 750×

Rys. 18 cd. Struktura ferrytyczna występująca w wytłoczce wkładki kumulacyjnej partii modelowej ze stali DC04 w obszarze pobocznicy (poziom 2) i w obszarze kielicha (poziom 3), jak zaznaczono na rys. 3; pow. 750×

Table 6. Results of HV1 hardness measurement of model batch drawpieces made of DC04 and 04J steel on sections transverse to the direction of stamping

Tabela 6. Wyniki pomiarów twardości HV1 wytłoczek partii modelowej ze stali DC04 i 04J na przekrojach poprzecznych do kierunku wytłaczania

Sample identification	HV 1 hardness measurement results	Mean value
	Imprints around the circumference	
Steel DC04		
Level closest to bottom	127, 126, 132, 122, 134, 123, 128, 127, 136, 126, 130, 122, 129, 132, 134	129
Central level	124, 124, 124, 124, 123, 125, 134, 132, 133, 130, 133, 128, 127, 129, 127, 124, 121, 120, 121, 119, 124, 127, 125, 128, 131	126
Level closest to cap	155, 152, 155, 152, 153, 155, 152, 153, 150, 155, 153, 161, 157, 160, 160, 155, 152, 150, 153, 155, 157, 154, 151, 157, 157, 151, 150, 158, 153, 153	154
Steel 04J		
Level closest to bottom	143, 142, 141, 139, 144, 137, 138, 138, 139, 140, 134, 140, 141, 145, 137, 137, 140, 144, 138, 139, 139, 137, 138, 137, 137	139
Central level	136, 147, 142, 138, 137, 136, 137, 140, 138, 138, 136, 141, 138, 138, 141, 150, 150, 157, 153, 153, 152, 153, 152, 155	145
Level closest to cap	161, 160, 162, 163, 158, 163, 158, 161, 163, 165, 171, 160, 161, 169, 163, 164, 159, 163, 167, 158, 175, 176, 168, 161, 165, 163, 168, 161, 165	164

According to the evaluation of ferrite grain size, carried out in accordance with the guidelines of the ATSM E112 standard, the average chord in the drawpieces of the model batch of the DC04 steel ranges from 17 to 19 µm, and that of 04J steel it is approx. 12 µm.

The results of hardness measurement (HV1 and HV0.5) of the model batch of DC04 and 04J steel drawpieces are presented in Table 6 (after stamping) and in Table 7 (after stamping and annealing at 650°C for 1 hour).

Table 7. Results of HV0.5 hardness measurement of DC04 and 04J steel drawpieces on sections perpendicular to the stamping direction after annealing at 650°C

Tabela 7. Wyniki pomiarów twardości HV0,5 wytłoczek ze stali DC04 i 04J na przekrojach poprzecznych do kierunku wytłaczania po wyżarzaniu w temperaturze 650°C

Sample identification	HV 0.5 hardness measurement results	Mean value
	Imprints around the circumference	
Steel DC04		
Level closest to bottom	112, 135, 119, 144, 110	124
Central level	154, 140, 114, 130, 126	133
Level closest to cap	148, 122, 124, 122, 110	125
Steel 04J		
Level closest to bottom	144, 128, 122, 137, 118	130
Central level	110, 146, 109, 109, 114	118
Level closest to cap	110, 117, 112, 95, 129	113

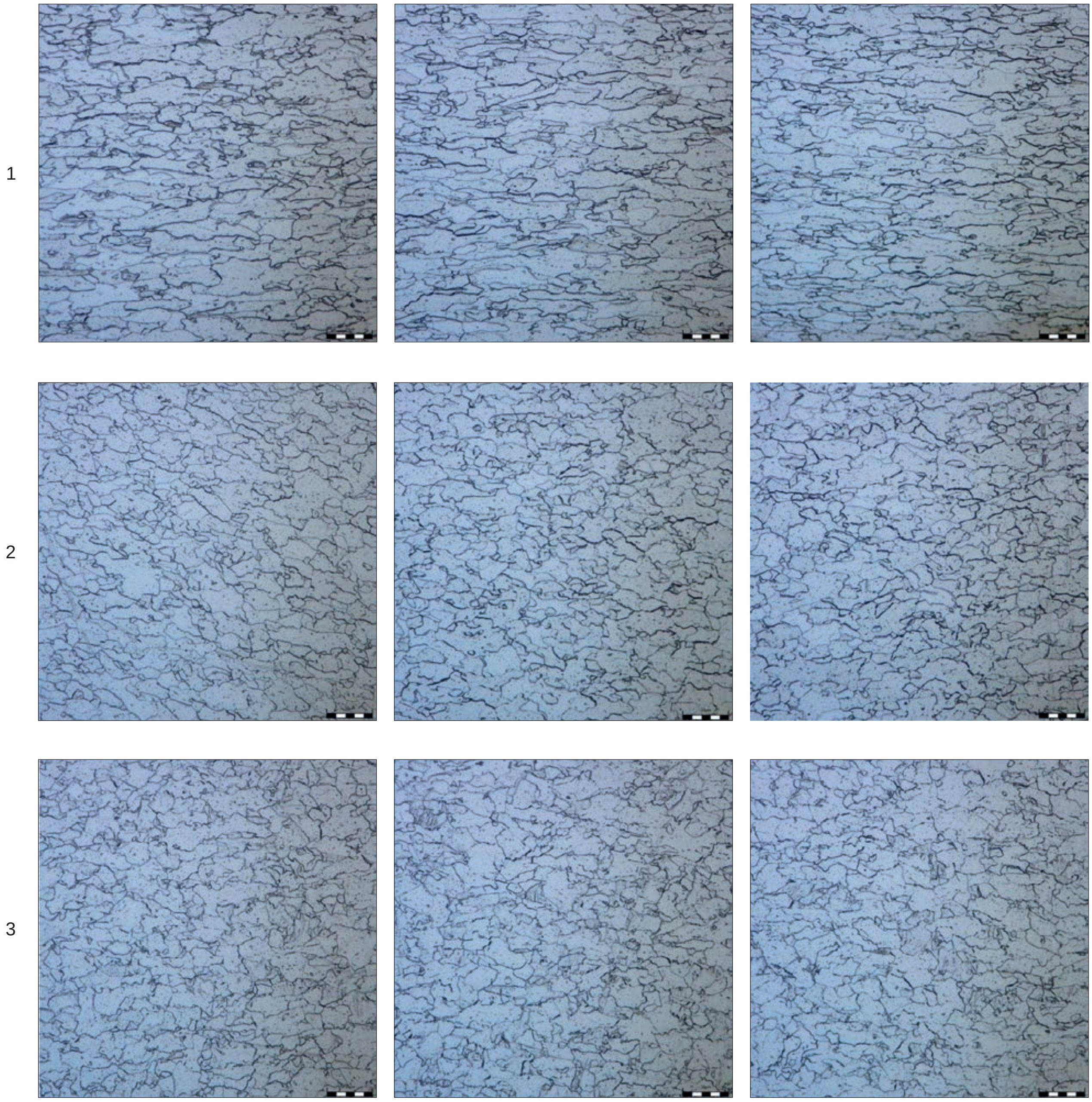

Fig. 19. Ferritic structure in the drawpiece of the 04J steel model batch liner in the bottom area (level 1), in the side surface area (level 2) and in the cap area (level 3), as indicated in Fig. 3 – magn. 750×

Rys. 19. Struktura ferrytyczna występująca w wytłoczce wkładki kumulacyjnej partii modelowej ze stali 04J w obszarze dna (poziom 1), w obszarze pobocznicy (poziom 2) i w obszarze kielicha (poziom 3), jak zaznaczono na rys. 3 – pow. 750×

The hardness of DC04 and 04J steel model batch drawpieces in the area of the bottom and the cap is different. In both cases, the hardness of the bottom area is lower than that of the cap area. For DC04 steel drawpieces it is 128.5 HV1 (bottom) and 154.3 HV1 (cap), and for 04J steel drawpieces it is 139.4 HV1 and 164.1 HV1(respectively). After annealing of the drawpieces, the hardness decreases in both steels and amounts to 124 to 133 HV0.5 in DC04 steel drawpieces, and from 113 to 130 HV0.5 in 04J steel drawpieces.

4. MEASUREMENT OF GEOMETRY OF MODEL BATCH LINER DRAWPIECES

The measurement of the drawpieces' geometry was taken using a Zeiss Vista coordinate measuring machine. The measurement was carried out for two drawpiece fasteners, and thus the external and internal shape of the drawpiece was analysed. The measurement was taken on 3 circles (each circle has 36 measurement points) at a distance of 5, 15 and 45 mm from the frontal surface (Fig. 24). The measured circles were used to determine roundness and concentricity deviations. The basis for determining the concentricity was a circle measured on the cylindrical part of the drawpiece, i.e. at the level of 5 mm.

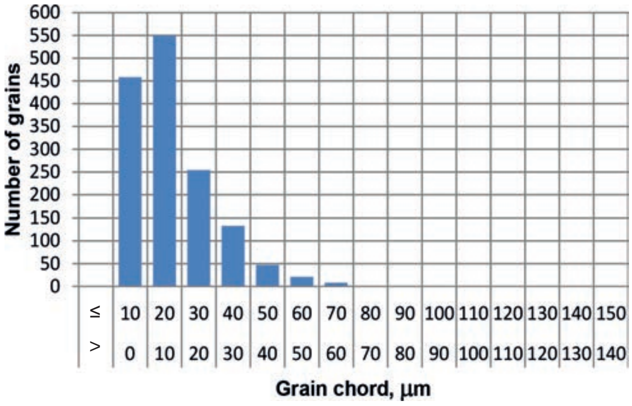

Fig. 20. Histogram of ferrite grain size distribution in DC04 steel drawpiece model batch revealed in direction transverse to the stamping within the cap area

Rys. 20. Histogram rozkładu wielkości ziaren ferrytu występujących w partii modelowej wytłoczek ze stali DC04 ujawnionych w kierunku poprzecznym do kierunku wytłaczania w obszarze kielicha

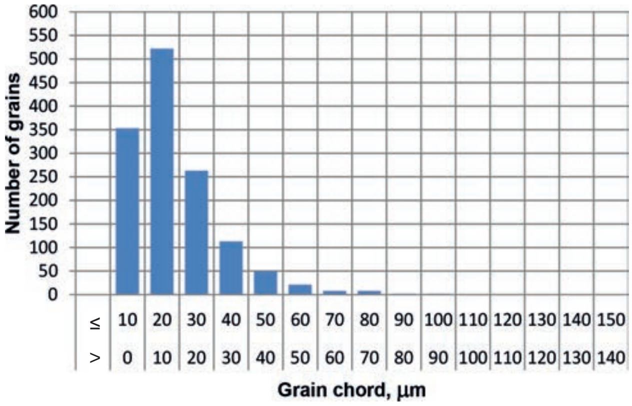

Fig. 21. Histogram of ferrite grain size distribution in DC04 steel drawpiece model batch revealed in direction transverse to the stamping within the bottom area

Rys. 21. Histogram rozkładu wielkości ziaren ferrytu występujących w partii modelowej wytłoczek ze stali DC04 ujawnionych w kierunku poprzecznym do kierunku wytłaczania w obszarze dna

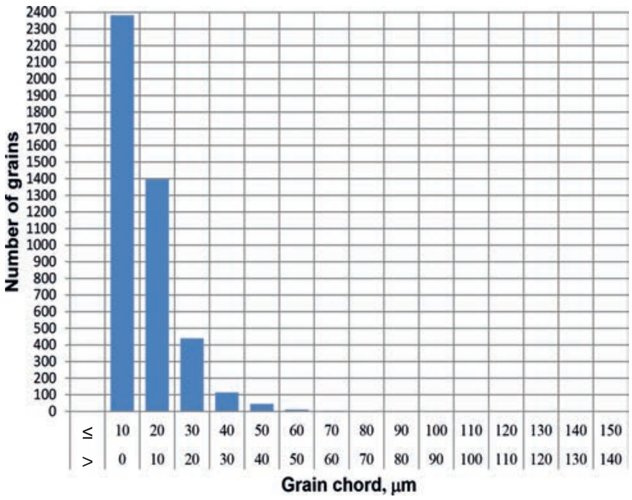

Fig. 22. Histogram of ferrite grain size distribution in 04J steel drawpiece model batch revealed in direction transverse to the stamping within the cap area

Rys. 22. Histogram rozkładu wielkości ziaren ferrytu występujących w partii modelowej wytłoczek ze stali 04J ujawnionych w kierunku poprzecznym do kierunku wytłaczania w obszarze kielicha

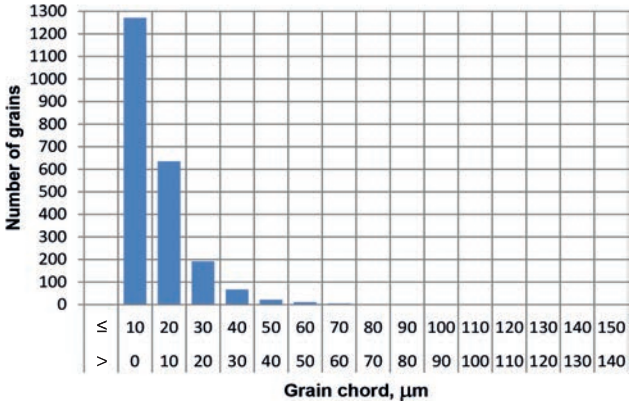

Fig. 23. Histogram of ferrite grain size distribution in 04J steel drawpiece model batch revealed in direction transverse to the stamping within the bottom area

Rys.23. Histogram rozkładu wielkości ziaren ferrytu występujących w partii modelowej wytłoczek ze stali 04J ujawnionych w kierunku poprzecznym do kierunku wytłaczania w obszarze dna

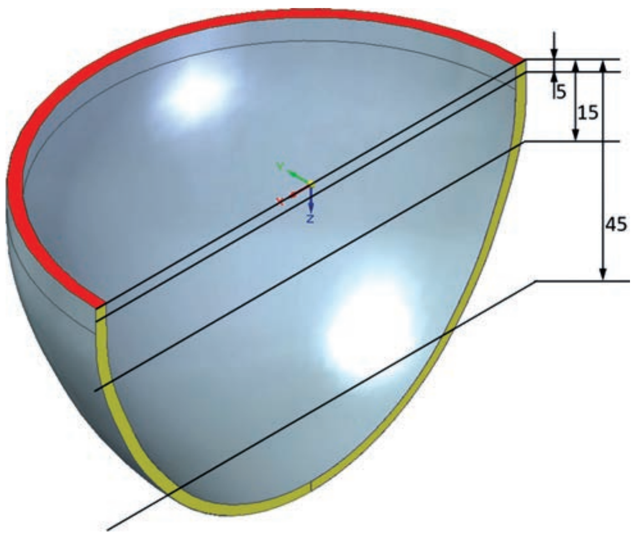

Fig. 24. Distribution of measurement surfaces

Rys. 24. Rozmieszczenie powierzchni pomiarowych

The scan of the profile of the drawpiece and outer surface of the drawpieces and the measurement of the wall thickness are shown in Fig. 25 (drawpieces A1, A2 and A3) and Fig. 26 (drawpieces B2 and B3). The results of measurement of deviations of the shape of roundness and concentricity of the liners at three levels of roundness and two of concentricity are presented in Table 8.

The wall thickness measured at three levels (5, 15 and 45 mm) in both tested drawpiece lots is variable. The thickest wall is in the area of the cap in the cylindrical part (5 mm level), and the thinnest wall is near the bottom (45 mm level). The wall thickness values are as follows:

- drawpieces **A**
– cap – 5 mm level 2.50–2.61, **avg. 2.55 mm**
– 15 mm level 2.29–2.60, **avg. 2.41 mm**
– bottom – 45 mm level 2.30–2.54, **avg. 2.39 mm**
- drawpieces **B**
– cap – 5 mm level 2.56–2.69, **avg. 2.60 mm**
– 15 mm level 2.34–2.50, **avg. 2.42 mm**
– bottom – 45 mm level 2.32–2.36, **avg.** 2.34 mm

Table 8. Results of measurement of deviations of the shape of roundness and concentricity of drawpieces for liners at three levels of roundness and two of concentricity

Tabela 8. Wyniki pomiarów odchyłek kształtu okrągłości i współśrodkowości wytłoczek na wkładki kumulacyjne na trzech poziomach okrągłości i 2 współśrodkowości

	Deviations of roundness and concentricity shape [mm]					
	INR	OTR	INR	OTR	INR	OTR
Liners	A1		A2		A3	
5 mm roundness level	0.079	0.045	0.082	0.052	0.078	0.084
15 mm roundness level	0.064	0.090	0.086	0.045	0.086	0.087
45 mm roundness level	0.118	0.078	0.133	0.145	0.155	0.196
Concentricity 1	0.094	0.093	0.081	0.095	0.102	0.115
Concentricity 2	0.234	0.305	0.137	0.151	0.007	0.314
Liners	B1		B2		B3	
5 mm roundness level	0.081	0.046	0.068	0.064	0.073	0.078
15 mm roundness level	0.098	0.042	0.098	0.073	0.067	0.070
45 mm roundness level	0.121	0.176	0.440	0.187	0.139	0.192
Concentricity 1	0.067	0.086	0.063	0.079	0.109	0.087
Concentricity 2	0.373	0.196	0.173	0.364	0.446	0.435

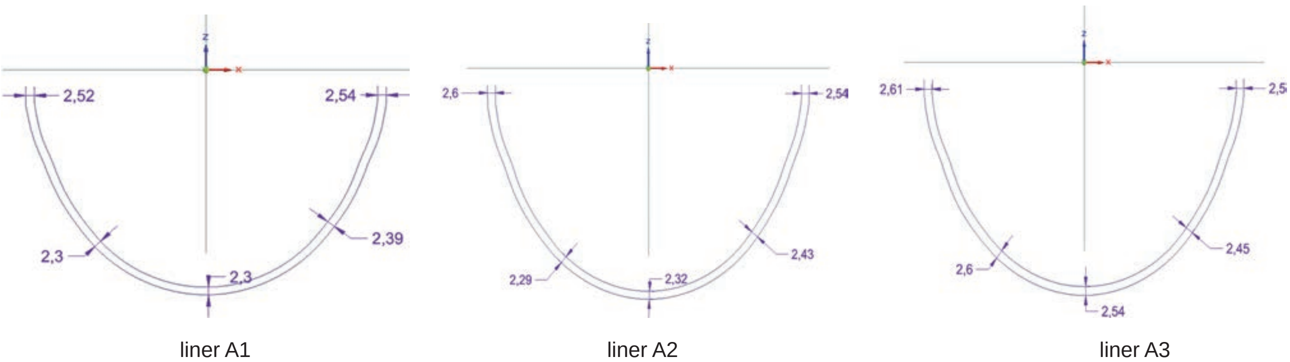

Fig. 25. Geometry of A1, A2 and A3 drawpiece surfaces and results of wall thickness measurement

Rys. 25. Geometria powierzchni wkładek A1, A2 i A3 oraz wyniki pomiarów grubości ścianek

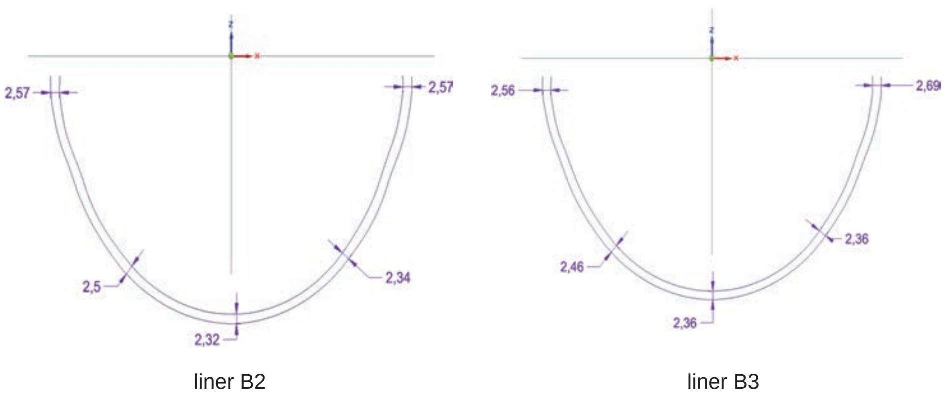

Fig. 26. Geometry of B2 and B3 drawpiece surfaces and results of wall thickness measurement

Rys. 26. Geometria powierzchni wkładek B2 i B3 oraz wyniki pomiarów grubości ścianek

The measurement of roundness and concentricity shape deviations shows a relatively large dispersion:

– deviation of roundness from 0.045 (5 mm level) to 0.440 mm (45 mm level)
– deviation of concentricity from 0.007 to 0.446 mm.

5. SUMMARY

The drawpieces for the semispherical liners with a diameter of 106.4 mm from the test and model batch were made on a PMS 160A excentric press with a pressure of 1.6 MN and a stroke of 20–140 mm using the equipment designed and manufactured under the project. The test batch of semi-spherical liner drawpieces with a diameter of 106.4 mm were made from steel discs with a diameter of 165 mm and a thickness of 2.5 mm made of DC04 and 04J steel. Using the selected technology, it was not possible to stamp the test batch from discs made of 004G steel. The probable cause was the insufficient surface quality of the discs and lower elongation (A: 12.8–14.8%), compared to discs made of DC04 and 04J steel (A: 35–44%), and too low load of the press.

The analysis of the ferrite grain shape shows that in cold-rolled sheets made of DC04 steel, in hot-rolled sheets made of 04J steel (ARMCO) and in cold-rolled strips made of 004G steel they are heterogeneous. In the strips annealed at 650°C, the ferrite grain size decreases and the grains take on more regular shapes. Based on the structure images revealed in three directions (along the rolling direction, at an angle of 45° to the rolling direction and perpendicular to the rolling direction), it was determined that in cold-rolled sheets made of DC04 steel, ferrite grains are larger, but more homogeneous in all three tested directions than in hot-rolled sheets of 04J steel and cold-rolled strips and those made of 004G steel and annealed at 650°C.

The presented evaluation of ferrite grain size shows that the average chord in sheets for DC04 steel liner test and model batches is approx. 21 μm, for 04J steel it is approx. 13 μm and in strips made of 004G steel after annealing at 650°C it is approx. 13.3 μm.

The results of measurement of mechanical properties in the three tested directions show a greater anisotropy of the mechanical properties is in 04J steel sheets and 004G steel strips than in DC04 steel sheets, but the differences in the tested values are small. A lower yield strength was achieved in sheets of steel DC04 (164–176 MPa) than in sheets of steel 04J (202–226 MPa) and strips of 004G (264–284 MPa). On the other hand, strips made of 004G steel were found to have a much lower elongation than sheets made of steels 04J and DC4. On average, in 004G steel strips, A_{80} was approx. 13%, and in DC04 and 04J steel sheets it was approx. 40%.

The grain size in the DC04 and 04J steel test batch liner drawpieces was evaluated in sections along the stamping direction. The analysis of the measurement results showed that the average chord in the drawpieces of the DC04 steel is over 21 μm, and in the drawpieces of the 04J steel liner it is 13 μm. The ferrite grains of the DC04 steel test batch drawpiece are larger and with more regular shapes than in 04J drawpieces. In the drawpieces of both tested steels, ferrite grains are finer in the bottom area than in the cap area.

The hardness of DC04 and 04J steel test batch drawpieces in the area of the bottom and the cap is different. In both cases, the hardness of the bottom area is lower than that of the cap area. In DC04 steel drawpieces it is 127.3 HV1 (bottom area) and 158.4 HV1 (cap area), and in 04J steel drawpieces it is 143.6 HV1 (bottom area) and 178.4 HV1 (cap area).

The ferrite grains revealed on the transverse cross-sections of the DC04 steel model batch liner drawpiece are larger and with more regular border shapes than in the 04J steel drawpieces.

The evaluation of ferrite grain size, carried out in accordance with the guidelines of the ATSM E112 standard with a μgrain software shows that the average chord in the drawpieces of the model batch of the DC04 steel ranges from 17 to 19 μm, and that of 04J steel it is approx. 12 μm.

The hardness of DC04 and 04J steel model batch drawpieces in the area of the bottom and the cap is different. In both cases, the hardness of the bottom area is lower than that of the cap area. For DC04 steel drawpieces it is 129 HV (bottom area) and 154 HV (cap area), and for 04J steel drawpieces it is 139 HV and 164 HV(respectively). After annealing of the drawpieces, the hardness decreases in both steels and amounts to 124 to 133 HV in DC04 steel drawpieces, and from 113 to 130 HV in 04J steel drawpieces.

REFERENCES

[1] W.P. Walters, J.A. Zukas. *Fundamentals of shaped charges*. New York: A. Wiley-Interscience Publication, 1989.

[2] D.C. Pack, W.M. Evans. Penetration by high-velocity ('Munroe') jets. *Proceedings of the physical society B*, 1950, 64 (4), p. 289.

[3] J. Janiszewski, E. Włodarczyk. Rola materiału wkładki w formowaniu strumienia kumulacyjnego. *Bulletin of MUT*, 2002, 51 (3), pp. 41-64.

[4] H.M. Kalia. *Penetration in granite by shaped charge liners of various metals*. Doctoral Dissertations, 1970, No. 2038.

[5] H. Nowak, D. Smoleński. *Ładunki kumulacyjne w wojsku, górnictwie i przemyśle*. Warszawa: Wydawnictwo MON, 1974.

[6] B. Bourne, K.G. Cowan, J.P. Curtis. Shaped charge warheads containing low melt energy metal liners. In: *Int. Symp. Ballistics Proc. 19th*, Switzerland, 2001, pp. 583–589.

[7] Z. Wilk, B. Zygmunt. Zastosowanie ładunków kumulacyjnych do perforacji odwiertów geologicznych. *Bulletin of MUT*, 2007, 56 (1), pp. 245–258.

[8] C.J. Poole, J.R. Ockendon, J.P. Curtis. Gas leakage from fragmentation warheads. In: *Proc. 20th Int. Symp. Ballistics*, Florida, 2002, pp. 113–117.

[9] T. Elshenawy, Q.M. Li. Influences of target strength and confinement on the penetration depth of an oil well perforator. *International Journal of Impact Engineering*, 2013, 54, pp. 130–137.

[10] A. Wojewódka, T. Witkowski. Metodyka modelowania procesu formowania strumienia kumulacyjnego wydłużonych ładunków materiałów wybuchowych. *Chemik* 2011, 65 (1), pp. 28–35.

[11] W. Burian, M. Magier, M. Rotkegel, J. Sobala, J. Szymała, A. Żak. Badania możliwości otworowania z wykorzystaniem ładunków kumulacyjnych. *Przegląd Górniczy*, 2016, 72 (7), pp. 20–25.

[12] A. Żak, J. Marcisz et al. Opracowanie składów chemicznych materiałów przeznaczonych do budowy wkładek kumulacyjnych oraz technologii ich wytwarzania. Łukasiewicz – IMŻ Research Project Report No. PI 0010 02-02 and PI 0010 02-04, December 2018 [unpublished].

[13] A. Żak, J. Marcisz, M. Burdek. Wykonanie testowych wkładek kumulacyjnych ze stopów na bazie Fe oraz przeprowadzenie badań na poligonie doświadczalnym. Report PI 0010 05 part 1, December 2019 [unpublished].

[14] J. Marcisz, A. Żak, T. Tomczak et al. Badania mikrostruktury i właściwości mechanicznych nowoopracowanych materiałów na bazie Fe przeznaczonych do wytwarzania wkładek kumulacyjnych. Łukasiewicz – IMŻ Study Report No. PI 0010 03-02 p. 1, December 2019 [unpublished].

[15] J. Marcisz, J. Stępień, T. Tomczak. Badania mikrostruktury i właściwości mechanicznych nowoopracowanych materiałów na bazie Fe przeznaczonych do wytwarzania wkładek kumulacyjnych. Łukasiewicz – IMŻ Study Report No. PI 0010 03-02 p. 2, December 2020 [unpublished].

[16] J. Stępień, M. Burdek. Wykonanie testowych wkładek kumulacyjnych ze stopów na bazie Fe oraz przeprowadzenie badań na poligonie doświadczalnym. Report PI 0010 05 part 2, December 2020 [unpublished].

[17] M. Burdek, J. Stępień. Opracowanie technologii wytwarzania wkładek kumulacyjnych z nowoopracowanych materiałów na bazie Fe. Report PI 0010 03 05 part 2, December 2020 [unpublished].

[18] J. Stępień, M. Burdek. Wykonanie testowych wkładek kumulacyjnych ze stopów na bazie Fe oraz przeprowadzenie badań na poligonie doświadczalnym. Report PI 0010 05 part 3, November 2021 [unpublished].

[19] ASTM E112-12: *Standard Test Methods for Determining Average Grain Size*.