M. WOJTASZEK*, P. CHYŁA*, T. ŚLEBODA*, A. ŁUKASZEK-SOŁEK*, S. BEDNAREK*

FEM MODELLING AND EXPERIMENTAL RESEARCH OF DIE FORGING OF Ni-Mo-Fe ALLOY ANTENNA COMPONENTS

MODELOWANE MES I BADANIA EKSPERYMENTALNE PROCESU KUCIA MATRYCOWEGO ELEMENTÓW KONSTRUKCJI ANTEN ZE STOPU TYPU Ni-Mo-Fe

This work was focused on the design of hot forging process for a selected element of Ni-Mo-Fe alloy. The research included numerical FEM simulation, testing in industrial conditions as well as laboratory tests. The numerical FEM simulation of hot forging of a selected forging was prepared and performed with application of QForm software. Next, the forging tests of the analyzed element were performed in industrial conditions, with application of the parameters used in the numerical simulation. The selected properties of the obtained forging were determined. The metallographic examination was also performed, including microstructure observation as well as the analysis of fractures formed during impact testing of specimens. Chemical composition of the investigated alloy was also examined during SEM-EDS characterization. The results of investigations were compared with the data obtained from FEM simulation, in order to specify the forging process parameters. The research showed, that the parameters of forging of the analyzed alloy assumed in the FEM numerical analysis and then verified in industrial conditions, allowed to produce a good quality product with quite uniform microstructure within its volume. No signs of porosity or micro-shrinkages were observed in the obtained product, what signifies, that the selection of forging parameters for the investigated material allowed to eliminate the casting defects present in the volume of a feedstock. Ni-Mo-Fe alloy product showing the strength and plastic properties allowing its application for the components of antennas was obtained by hot forging.

Keywords: Ni-Mo-Fe alloy, die forging, numerical simulation, microstructure, properties

Celem podjętych badań było zaprojektowanie procesu kucia na gorąco wybranego elementu ze stopu nikiel – molibden – żelazo. Zakres badań obejmował symulację numeryczną MES, próby w warunkach przemysłowych oraz badania laboratoryjne. Przygotowano oraz przeprowadzono symulację numeryczną MES procesu kucia na gorąco wybranej odkuwki, z wykorzystaniem programu QForm. Następnie przeprowadzono próby kucia analizowanego elementu w warunkach przemysłowych, stosując takie same parametry jak przyjęto podczas analizy numerycznej. Określono wybrane właściwości otrzymanej odkuwki. Przeprowadzono badania metalograficzne, które objęły obserwację mikrostruktury oraz ocenę przełomów powstałych podczas udarowego łamania próbek. Wykonano też analizę składu chemicznego materiału metodą EDS. Przyjęte do analizy numerycznej MES i następnie zweryfikowane w warunkach przemysłowych parametry procesu kucia analizowanego stopu pozwoliły na otrzymanie odkuwki o właściwym przerobie oraz dość jednolitej w objętości mikrostrukturze. Na zgładach metalograficznych pobranych z różnych obszarów odkuwki nie zaobserwowano porowatości ani rzadzizn. Przyjmuje się, że poprawny dla badanego materiału dobór parametrów kucia pozwoliła na usunięcie obecnych w objętości wsadu wad odlewniczych. W procesie kucia matrycowego na gorąco przy zaproponowanych parametrach otrzymano wyrób, którego właściwości mechaniczne pozwalają na jego zastosowanie w roli elementów anten.

1. Introduction

The most important fields of application of modern soft magnetic materials include radioengineering, telecommunications, construction of measuring apparatus, as well as where the processing and transport of electric energy takes place, with required sensitivity to low magnetic field [1]. The materials meeting these requirements include Ni-based alloys. Nickel is a ferromagnetic metal, however, its magnetic properties decay after exceeding the temperature of 353°C. It is also resistant to corrosion in atmosphere, sea water and organic acids environments. Ni-based alloys containing the addition of Fe show low coercive force, high magnetic permeability [2] and narrow hysteresis loop. Since nickel influences the thermal expansion of iron significantly, the Ni-Fe alloys also show a low thermal expansion coefficient [3]. The increased strength and good fracture toughness are

* FACULTY OF METALS ENGINEERING AND INDUSTRIAL COMPUTER SCIENCE AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, 30-059 KRAKÓW, 30 MICKIEWICZA AV., POLAND

other advantages of these alloys [4]. Commercial significance of magnetic materials is partly connected with their specific application in the construction of antennas, where interference-free working is required in different, sometimes aggressive environments, such as soil or seawater. Such specific elements are required to show the above mentioned magnetic properties, as well as the resistance to environmental corrosion. In selected cases, heat resistance is also required. Molybdenum and copper increase the corrosion resistance of nickel, while molybdenum alone additionally contributes to its strengthening. The addition of Si increases the heat resistance of an alloy.

The magnetic properties of a product result not only from the chemical composition of a material, but also from other factors such as proper crystal arrangement and the absence of internal microstresses. The uniform density is also important, thus requiring the elimination of casting structural defects such as micro-shrinkage and porosity. Meeting these requirements depends on the production technology and the applied technological parameters. The alloys under discussion are mostly produced by casting and subsequent plastic working. However, there are also examples of powder metallurgy methods such as hot compaction, applied to the production of these alloys, given in the literature [5, 6].

In case of the application of plastic working process, such as die forging, to the forming of Ni-Mo-Fe alloy products, while having a suitable knowledge about the material's rheology, it is possible to model the forming process and perform its numerical analysis giving effective strain and mean stress distribution. In case of forging processes, the proper tool for the realization of this objective is the finite element method (FEM). The examples of FEM suitability for the design of die forging technology are presented in [7-11].

2. Research

2.1. Objective and scope of research

The objective of the realized investigations was the design of hot forging process for a selected element of Ni-Mo-Fe alloy. The scope of research included numerical FEM simulation, testing in industrial conditions as well as laboratory tests. The numerical FEM simulation of hot forging of a selected forging was prepared and performed with application of QForm software. Next, the forging tests of the analyzed element were performed in industrial conditions, with application of the parameters used in the numerical simulation. The selected properties of the obtained forging were determined. The

metallographic examination was also performed, including microstructure observation as well as the analysis of fractures formed during impact testing of specimens. The results of investigations were compared with the data obtained from FEM simulation, in order to specify the forging process parameters.

2.2. Material under investigation

As the material to be analyzed, Ni-Mo-Fe alloy rod with diameter of 30 mm and lenhth of 200 mm in as-cast condition was selected. The chemical composition of the material is given in Table 1. Silicon and manganese were introduced in order to increase the castability of the alloy and to improve the leakproofness of moulds.

TABLE 1

Chemical composition of the alloy under investigation

component	Ni	Mo	Fe	Si	Mn	C	O	N
content, %	73	12	10	2.7	0.4	0.05	0.1	0.005

The casting in a form of a bar showed high porosity [7], thus being unsuitable for the application as a material for structural components. The view of a bar which cracked during the attempt of being forged with improperly selected parameters, is presented in Fig. 1, together with the fractures formed as a result of decohesion.

2.3. Characterization of antenna component forging

The shape and dimensions of a forging under investigation were selected basing on the requirements for the antennas [7]. The characteristic dimensions of a final product are shown in Fig. 2, while Fig. 3 presents a numerically generated model of a forging with a flash.

2.4. Numerical FEM simulation of forging process

The aim of the performed simulation was obtaining effective strain and mean stress distributions in the analyzed forgings and resulting from this simulation evaluation of the assumed parameters of forging process and possibilities of removal of casting defects of the Ni-Mo-Fe alloy ingot.

The commercial software QForm3D, based on the finite element method, was used to the analysis of forging process. It allows to perform thermomechanical simulation of metal forming processes in three-dimensional state of strain. The technological data concerning forging the antenna were prepared on the basis of technological knowledge of the forging process and also basing on the
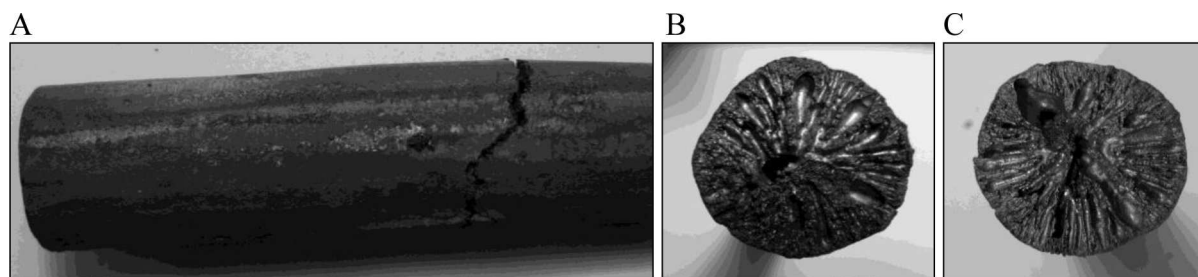
Fig. 1. Ni-Mo-Fe material after forging with improperly selected parameters; A – cracked feedstock; B, C – view of fracture surfaces
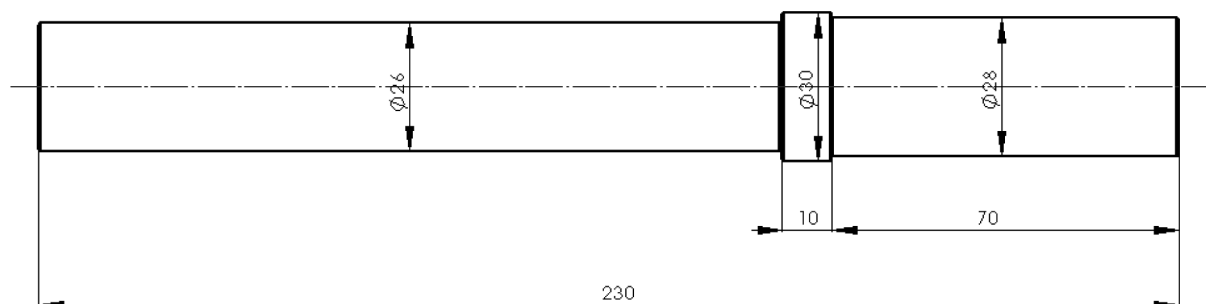

Fig. 2. Shape and dimensions of antenna

Fig. 3. Numerically generated model of a forging with a flash

analysis of previous research works concerning forging of nickel based alloys. Therefore, the simulation assumed the feedstock temperature of 1100°C, and heating and holding time as 35 minutes. Next, the simulation also contained placing the bar in a die cavity heated to the temperature of 300°C, and subsequent forging on MPM 2000 hammer in a single operation. The calculations were performed for the ingots of 30 mm diameter and 210 mm length. The friction factor between tools and material being deformed was assumed to 0.4. The physicochemical properties of a material being deformed were assumed according to the data obtained from compression tests of the alloy under investigation.

Figs. 4 and 5 present the results of numerical calculations, in the form of effective strain (Fig. 4) and mean stress (Fig. 5) distributions in the characteristic sections of a forging. The highest levels of effective strain are observed in circumferential regions of a forging as well as within a flash. Starting from a flash land, these values are 2-3 times higher than those observed at forging axis.

Fig. 5 shows the distribution of mean stresses in the analogous sections. Compressive stresses are dominant within the forging, which should facilitate the levelling of casting defects occurring in the volume of a feedstock, i.e. mainly micro-shrinkages and voids. Within the flash region, the resultant mean stresses are the lowest ones, which qualitatively corresponds with the obtained microstructure (Fig. 10).
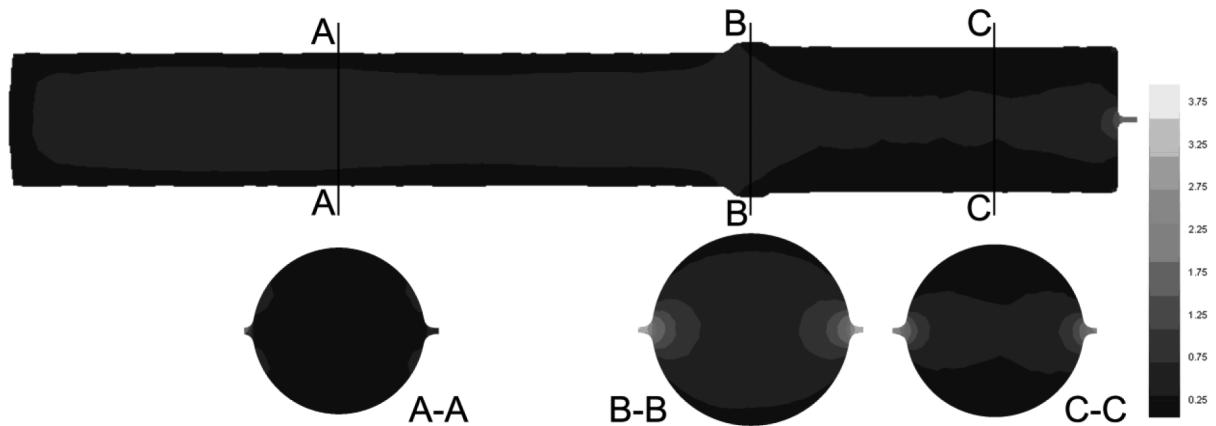
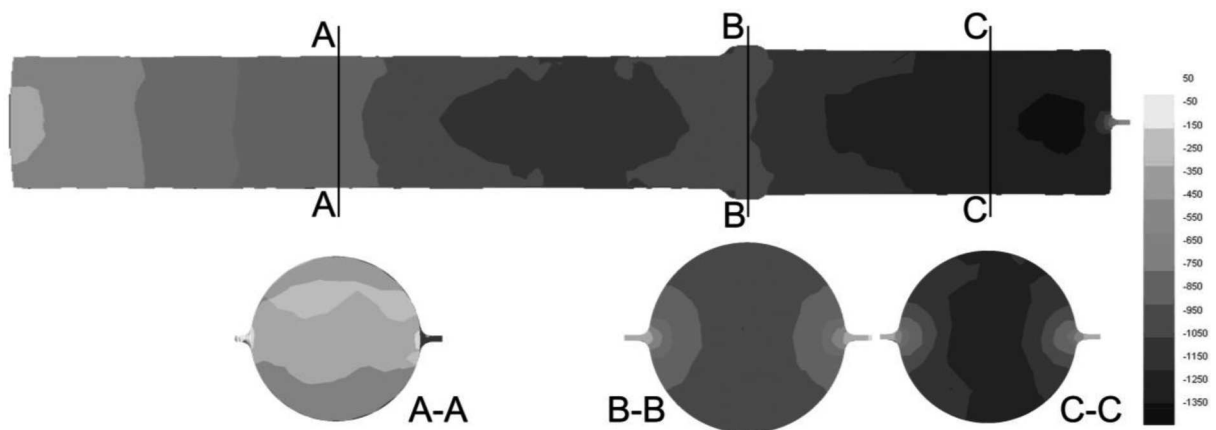Fig. 4. Effective strain distribution in characteristic sections of a forging

Fig. 5. Mean stress distribution (MPa) in characteristic sections of a forging

2.5. Forging manufacturing test in industrial conditions

The forging test in industrial conditions was performed in Wolbrom Forging Plant. Ø 30×210 mm cast bar was used as a forging feedstock, which corresponded to that assumed in FEM analysis. The flash was not removed, considering the necessity of performing scheduled investigations within the whole volume of a forging.

For the obtained forging, hardness measurements were made on the cross-section of the obtained forging on perpendicular and parallel axis of symmetry of forging in different distances from the surface of the forged part. For the material in as-forged state, true stress-true strain curves were constructed basing on the results of uniaxial compression test realized at room temperature. In order to examine the material's ductility in the dynamic loading conditions, impact tests were performed. The metallographic examination was carried out, including microstructure observation as well as the analysis of fractures formed during impact testing of specimens.

The chemical composition analysis of a material was also performed, with application of EDS method.

2.6. Results of investigations of selected properties of a forging

Hardness was measured using the Brinell method, in two perpendicular directions on the forging cross section, in different distances from its axis. The scheme showing the layout of hardness measurements is presented in Fig. 6. Four measurements were made for each location and the averaged results are collected in Fig. 7. The hardness values measured at all locations along the vertical axis as well as at the internal points located along the horizontal axis (locations 1-3) were comparable, with the average level of approx. 171 HB. In case of the locations along the horizontal axis situated near the outer surface of a forging, the hardness increased towards the edge (locations 4 and 5). The highest average hardness, amounting to 184±4.57 HB, was measured at the location 5, i.e. in the horizontal forging axis, within the region directly adjacent to the flash.
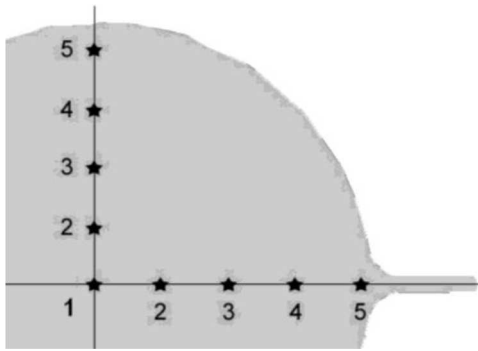
Fig. 6. Scheme of HB hardness measurements layout on the forging cross section

Impact tests were realized using Charpy pendulum machine, applying U-notched specimens. The average impact strength amounted to 872 ± 27 kJ/m^2.

Uniaxial compression test was carried out at room temperature, applying the strain rate of 1 s^{-1}. The specimens of 5 mm diameter and 6 mm height were subjected to compression. The obtained results are collected in Table 2. Fig. 8 presents the example curves describing the variations of force as a function of displacement (Fig. 8A) and true stress as a function of true strain (Fig. 8B), constructed basing on the results of compression test. The compression samples did not crack during compression tests, so compressive strength could not be determined. Young's modulus calculated basing on test results amounted to 118 ± 30 GPa, and the yield strength $R_{p0.2} = 326\pm20$ MPa.
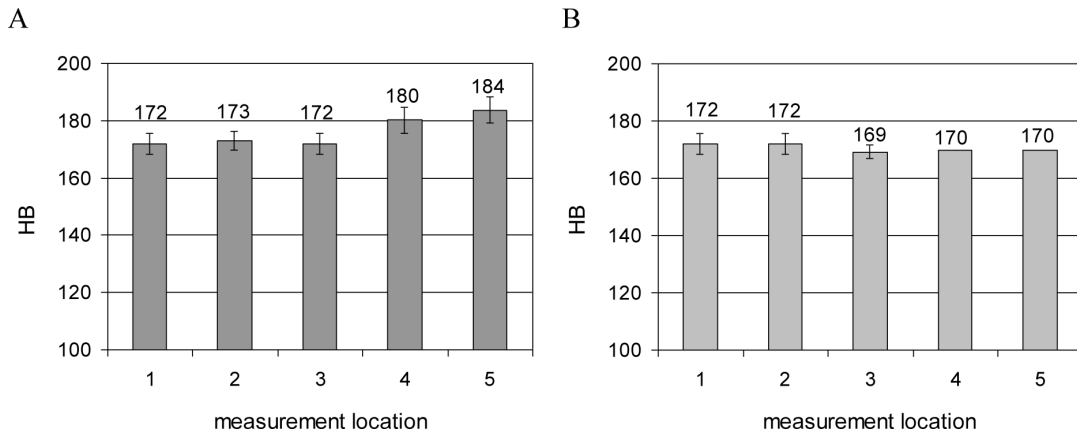

Fig. 7. HB hardness on the forging cross section, measured along: A – horizontal axis, B – vertical axis

TABLE 2

Parameters of uniaxial compression test and the determined alloy properties

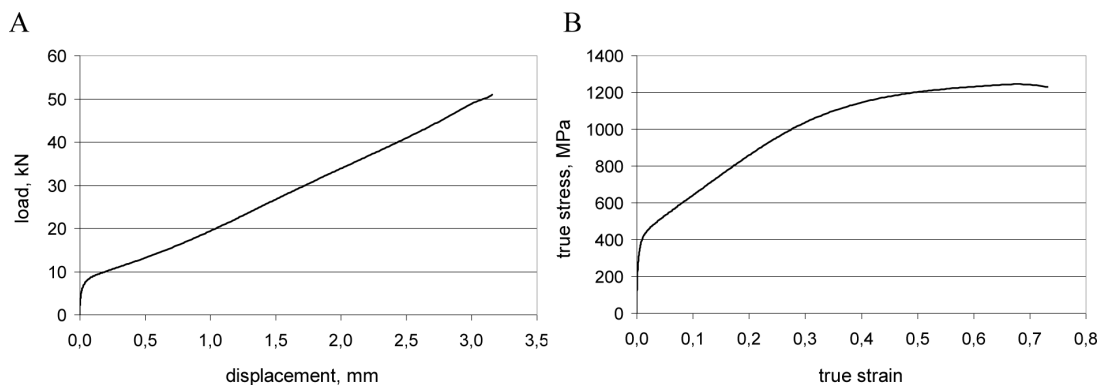| specimen no.	testing temperature °C	strain rate s^{-1}	d_0 mm	h_0 mm	S_0 mm^2	$F_{0.2}$ N	E GPa	$\overline{E}$ GPa	$R_{0.2}$ MPa	$\overline{R}_{0.2}$ MPa
1			5,00	6,02	19,63	6580	104	118	335	326
2	20	1	5,01	6,03	19,71	6400	127	±	325	±
3			5,00	6,01	19,63	6270	122	30	319	20

Fig. 8. Variations of: A – force as a function of displacement, B – true stress as a function of true strain, obtained from compression test at room temperature

2.7. Metallographic examination

The examination included observations of microstructure as well as fracture surfaces formed as a result of impact test. Optical microscopy was applied to examine the state of microstructure of a forging. Metallographic specimens were subjected to etching. The observations were carried out on longitudinal and cross sections, in the characteristic regions of a forging. Fig. 9 presents schematically the regions selected for metallographic examination with the designations assigned to them, while Fig. 10 shows the photographs of a microstructure of the forging.

The microstructure observed on metallographic specimens is fine-grained and some inhomogeneities result from casting process. The size and orientation of grains depend on the region selected for examination. The surfaces of specimens do not exhibit any pores, which are typical for the as-cast material. This testifies

for a proper processing of a feedstock in the forging process, under the assumed process parameters.
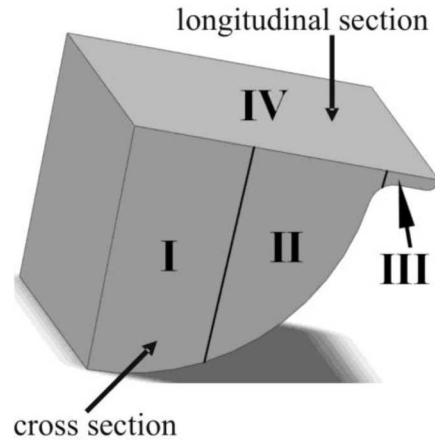

Fig. 9. Scheme of sections selected for microstructure analysis; I-III – cross sections, IV – longitudinal section
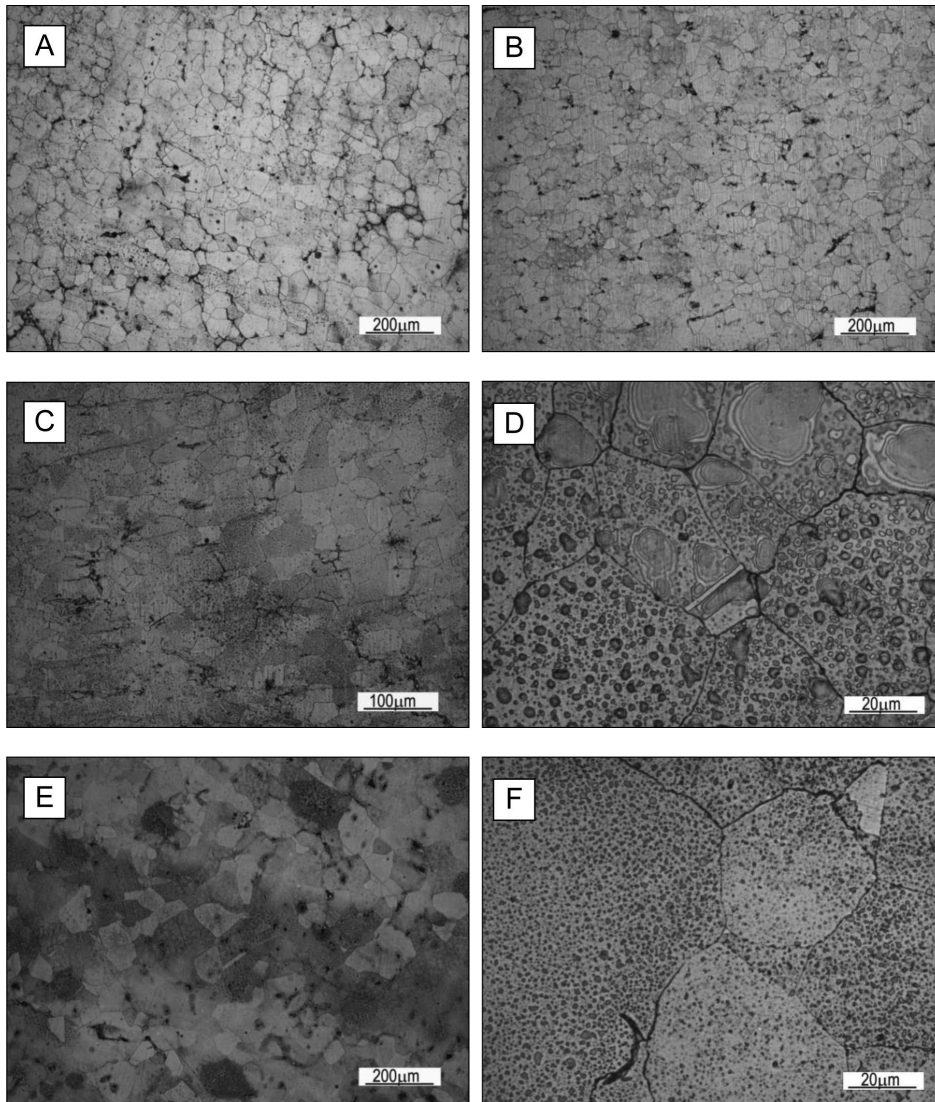

Fig. 10. Microstructure of forged at 1200°C Ni-Mo-Fe alloy; regions: A – I, B – II, C,D – III, E,F – IV; etched sections
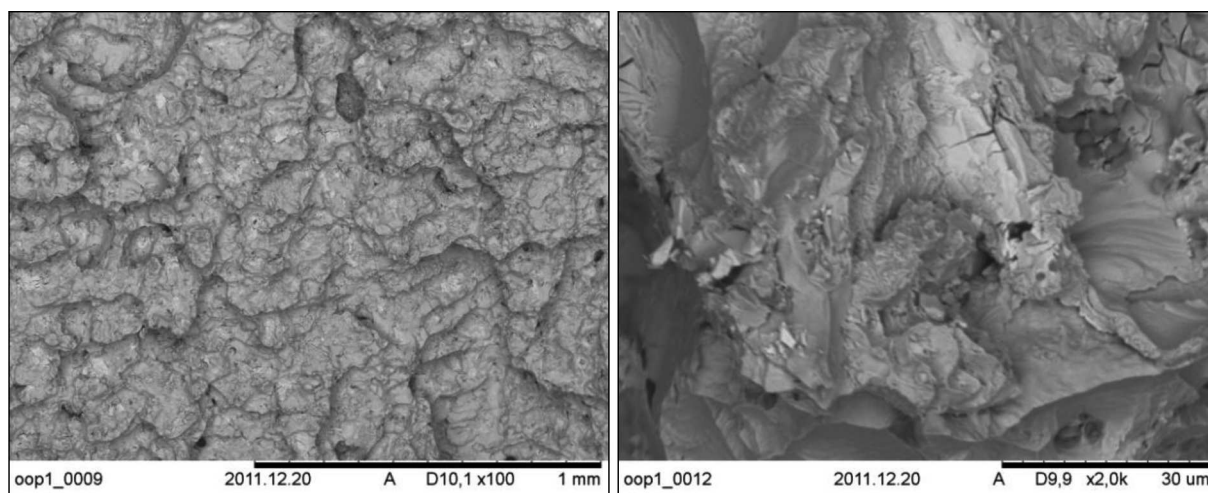
Fig. 11. Surfaces of fractures obtained during impact testing of a specimen forged at 1200°C

The surfaces of fractures obtained during impact testing were observed with application of scanning electron microscopy (SEM), using the Hitachi TM3000 microscope. The fractography of fracture surfaces is presented in Fig. 11. The observed fractures exhibit ductile character.

2.8. Analysis of chemical composition

The qualitative and quantitative analysis of chemical composition was performed with application of EDS method (energy-dispersive X-ray spectroscopy), using the Hitachi TM3000 scanning electron microscope equipped with a suitable software. The fracture surfaces obtained during impact testing were analyzed. Fig. 12 presents the distribution of elements within the randomly selected region on the fracture surface. The results of quantitative analysis are presented in Fig. 13. The contents of basic components determined with EDS method (Fig. 14), for a forging of the analyzed alloy, were close to those given by the manufacturer of a casting. The differences in contents of the individual elements depend on the location where the analysis is being performed.
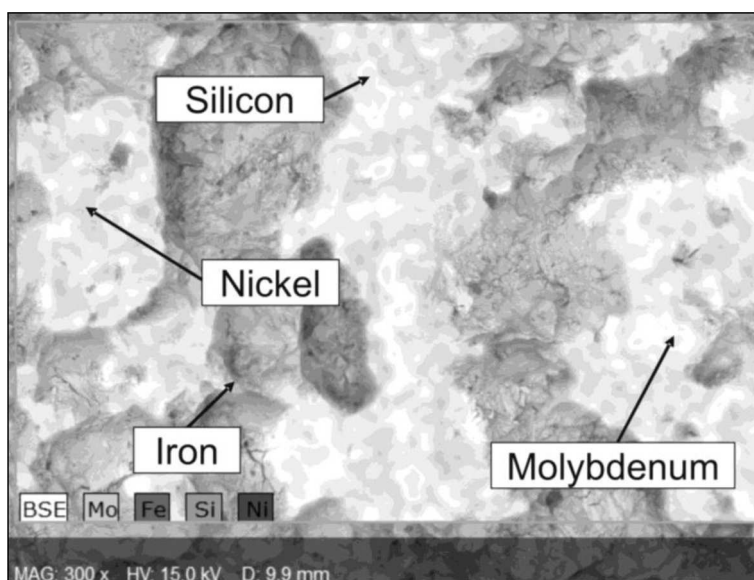

Fig. 12. Distribution of elements within the randomly selected region on the fracture surface obtained during impact testing
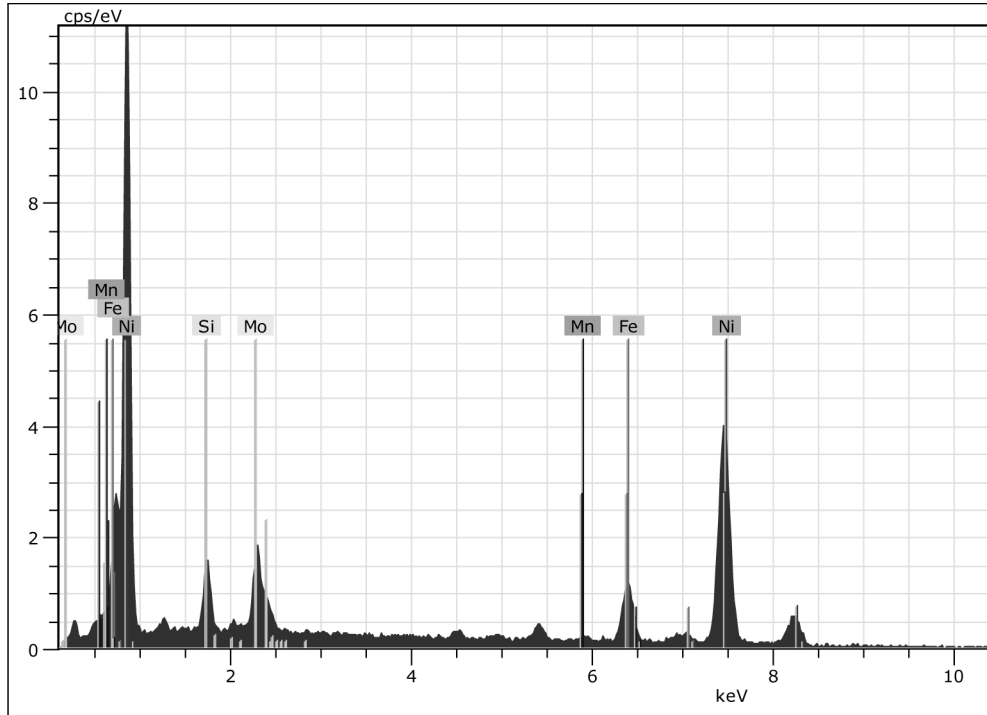
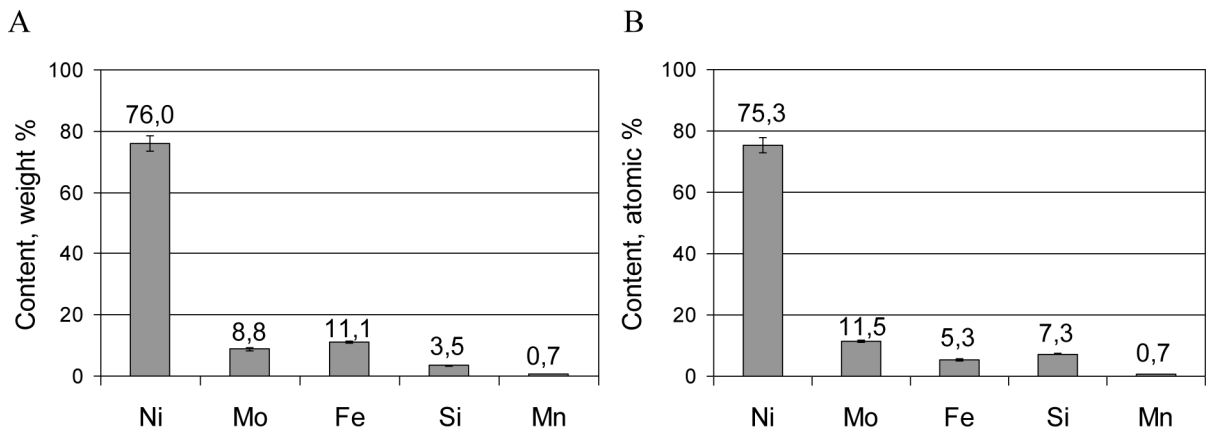Fig. 13. Diffraction pattern of a specimen forged at 1200°C

A

B

Fig. 14. Results of EDS quantitative analysis of the contents of basic elements in a specimen forged at 1200°C; A – mass fraction, B – volume fraction

3. Conclusions

Basing on the information obtained from the FEM simulation of hot die forging of as-cast feedstock of Ni-Mo-Fe alloy, as well as on the results of testing of selected properties of a forging produced in industrial conditions, applying the parameters elaborated using the data from numerical analysis, it can be concluded as follows:

1. The parameters of forging of the analyzed alloy assumed in the FEM numerical analysis and then verified in industrial conditions, allow to produce a forging showing the proper degree of working and quite uniform microstructure within its volume.

2. The analysis of results of numerical calculations, for the assumed boundary conditions, allows to observe that the highest levels of effective strain occurred in circumferential regions of a forging and within a flash. This is confirmed by hardness measurements performed within these regions, especially in a circumferential zone.

3. The die forging of the alloy under investigation in as-cast state leads to the satisfying results, considering the microstructure. No signs of porosity or micro-shrinkages were observed on the metallographic specimens prepared from different regions of a forging. It is assumed that the selection of forging

parameters, being adequate for the investigated material, as well as the negative resultant mean stress acting within the forging, allowed to eliminate the casting defects occurring in the volume of a feedstock.

4. During the realization of a hot die forging process with the proposed process parameters, a product was obtained showing the properties allowing to use it in the construction of antennas.

The realized numerical analysis as well as the investigations of the properties of a forging will contribute to the development of research program concerning the alloy under analysis. The results presented in the work are limited to the aspects of design and assessment of the alloy's selected mechanical properties and microstructure. However, considering the proposed application of the alloy, the analysis of magnetic properties of the material in as-forged state is indispensable. Moreover, further research concerning the new variants of forging conditions could be advisable, in order to improve the efficiency of the elimination of casting defects.

REFERENCES

[1] M. P l a z a, L. P e r e z, M.C. S a n c h e z, Reducing the losses in sintered permalloy by addition of ferrite, Journal of Magnetism and Magnetic Materials **309**, 207-211 (2007).

[2] J. L e e, Y. K a n g, Processing of bulk nanostructured Ni–Fe materials. Scripta Materialia **44**, 1591-1594 (2001).

[3] J.L. M c C r e a, G. P a l u m b o, G.D. H i b b a r d, U. E r b, Properties and applications for electrodeposited nanocrystalline Fe-Ni alloys. Reviews on Advanced Materials Science **5**, 252-258 (2003).

[4] H. L i 1, F. E b r a h i m i, Tensile behavior of a nanocrystalline Ni–Fe alloy, Acta Materialia **54**, 2877-2886 (2006).

[5] J. F ü z e r, P. K o l l a r, D. O l e k s a k o v a, S. R o t h, Soft Magnetic Properties in Bulk Permalloy Alloys Fabricated by a Warm Consolidation. Acta Physica Polonica A **113**, 1, 59-62 (2008).

[6] D. O l e k s a k o v a, S. R o t h, P. K o l l a r, J. F ü z e r, Soft magnetic properties of NiFe compacted powder alloys. Journal of Magnetism and Magnetic Materials **304**, 730-732 (2006).

[7] P. S k u b i s z, H. A d r i a n, J. S i ń c z a k, Controlled cooling of drop forged microalloyed steel automotive crankshaft. Archives of Metalurgy and Materials **56**, 1, 93-107 (2011).

[8] P. S k u b i s z, A. Ł u k a s z e k - S o ł e k, J. K o w a l s k i, J. S i ń c z a k, Closing the internal discontinuities of ingots in open die forging. Steel Research International **79**, 555-562 (2008).

[9] J. S i ń c z a k, P. S k u b i s z, M. P i e t r z y k, A. Ł u k a s z e k - S o ł e k, Analysis of microstructure evolution in the forging of a windmill main shaft. Steel Research **8**, 583-589 (2006).

[10] P. S k u b i s z, J. S i ń c z a k, Precision forging of thin-walled parts of AZ31 magnesium alloy, Archives of Metallurgy and Materials **52**, 329-336 (2007).

[11] A. Ł u k a s z e k - S o ł e k, J. S i ń c z a k, S. B e d n a r e k, Advanced estimation of tool life in backward extrusion by means of FEM simulation. Steel Research International **2**, 1-6 (2008).