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APPLCATION OF NICKEL SUPERALLOYS ON CASTINGS FOR CONVENTIONAL ENERGY EQUIPMENT ITEMS

Zenon Pirowski

Foundry Research Institute,
Poland, 31-418 Krakow, 73 Zakopiańska Street

Summary. The actions that can mitigate the adverse effects of various energy crises are continuous improvements in the efficiency of power generation plants. This can be achieved by carrying out the processes at an always higher temperature and pressure, and in a more aggressive environment than the parameters used so far. Such requirements cannot be satisfied any longer by the iron-based alloys, even the best ones. Therefore, multi-component alloys based on nickel and cobalt start to be the materials of choice. On the other hand, new materials of higher performance life are searched for all the time.

Jointly with its American partners, the Foundry Research Institute in Krakow carries out the research works which, among others, aim at the conversion of both material and techno-logy from structures forged and welded in nickel superalloys to cast elements for operation under the most demanding conditions of the power plants of a new generation. A part of the research is done under an “A-USC - NICKEL” American programme, to participation in which the Foundry Research Institute has been invited. Within this programme, the initial studies have already been carried out to master the technique of melting and casting the Inconel 740 alloy and preliminary material testing has been performed on the ready castings. It has been stated, among others, that with the temperature increase, particularly above 700°C, this alloy when used as a cast material is characterised by a definitely less drastic decrease of tensile strength than the same alloy subject to plastic forming.

Key words: cast nickel superalloys, manufacturing technology, mechanical properties, microstructure, dispersion hardening.

INTRODUCTION

Notwithstanding the development of power industry based on different methods of energy generation, the prevailing technique continues to be that which uses coal as a main source of energy. Forecasts in this field predict that this situation will continue in coming decades, as evidenced by the repeated oil and gas crises, not to mention the recent events in Japan.

The actions that can mitigate the adverse effects of such crises are continuous efforts to increase the efficiency of power plants and develop the techniques of coal gasification. By increasing the efficiency of plants from 37% to 46%, and by raising the temperature to 760°C and pressure to 35 MPa, the amount of the emitted CO_2 is reduced by 22% (Figure 1). The amount of other pollutants introduced to the environment decreases as well. The consequence is cost reduction and less of waste disposed to the environment.

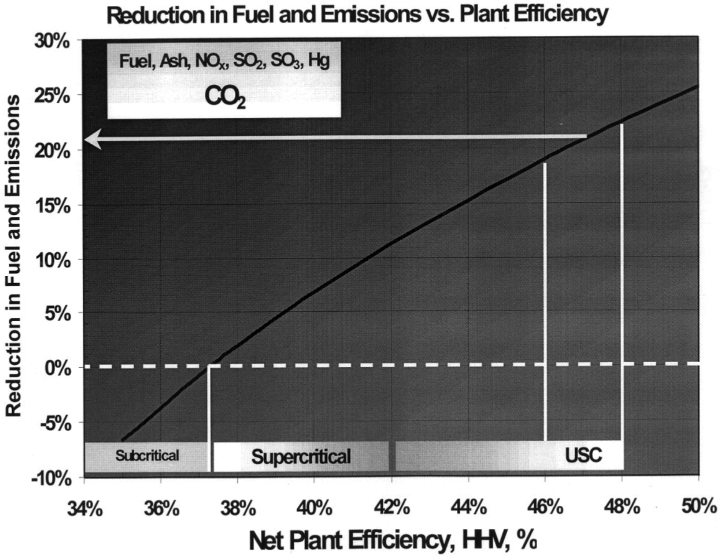


Fig. 1. Effect of operational efficiency of power plants on the emission rate of greenhouse gases (according to data obtained from an American partner – co-executor of the project)

In Poland the share of coal plants in electricity production is over 90%. Therefore, introduction of technological innovations is the action of strategic importance for operation of the national economy and energy security in our country.

Coal processing techniques, both simple consisting in its combustion, as well as complex, such as e.g. gasification, require plants, which include cast parts operating at very high temperatures and in aggressive environments. Increasing the operational efficiency of these devices is a way to reduce the emissions of CO_2 and other pollutants. This can be obtained by conducting the processes at always higher temperatures and pressures, and in more aggressive media than those used up to now. These requirements cannot be satisfied by the iron-based alloys, even by those of the best quality, and therefore complex superalloys based on nickel and cobalt are applied. They can carry loads at temperatures higher even than 80% of their melting point and in much more aggressive environments. These materials include, among others, nickel superalloys. Within this family of alloys, new materials of improved performance life are developed. The cooperation of materials scientists with designers and process engineers results in the creation of new equipment, more efficient and thus more friendly to the environment.

The Foundry Research Institute in Krakow, jointly with its American partners, has been conducting a research, the main objective of which is to investigate the possibilities of conversion of both material and technology from structures forged and welded in nickel superalloys to cast elements for operation under the most demanding conditions of the power plants of a new generation. A part of the research is done under an “A-USC - NICKEL” American programme, to participation in which the Foundry Research Institute has been invited.

RESEARCH MATERIAL

After agreements made with the U.S. partners, it has been decided to start the research with the Inconel 740 alloys.

Inconel 740 is a new nickel-chromium-cobalt superalloy. It is solution heat treated and aged, which makes it precipitation hardened with the dispersed inclusions of the second phase. It has been developed for high temperature operation in the automotive and energy industries. Its use increases the service life of boilers, pipes, valves and exhaust systems for diesel engines.

The nickel alloy matrix is solution hardened with an addition of cobalt. During operation at high temperatures, the additions of niobium, aluminium and titanium in the form of precipitates coherent with the matrix of γ'phase dispersion harden the alloy.

Inconel 740 has excellent resistance to high-temperature corrosion. The high content of chromium makes this alloy resistant to oxidation, carburisation and sulphurising, while the high content of nickel and low level of iron make it resistant at high temperatures to the effect of halides (salts of hydrogen halide acids: fluorides, chlorides, bromides and iodides).

In the case of alloys used for coal-fired boilers, a resistance to the corrosive effect of coal dust is also required, and it is Inconel 740 that can satisfy this requirement.

RESEARCH

Nickel alloys are a group of materials which in the liquid state tend to react strongly with the ceramic material of both crucible and foundry mould.

At the present stage of studies, the work has been started on the selection of optimum ceramic materials which contact the liquid Inconel 740 alloy. The first idea was to use for melting an induction furnace with an inert crucible lining (based on Al_2O_3) and as a moulding material – the ceramics with silicate binders. Yet, the obtained test ingots contained some defects, i.e. the discontinuities present in the cast material, mainly in the form of non-metallic inclusions, often forming very large oxide films.

Nickel superalloys, Inconel 740 included, contain a significant amount of the alloying additives of aluminium and titanium (often more than 2%). These elements at high temperatures are highly reactive and “willingly” combine with oxygen. Therefore, a very important metallurgical treatment during melting is reducing to maximum the content of oxygen dissolved in liquid alloy. For this purpose, the methods such as deoxidising with special magnesium-containing deoxidisers and restricted access of air to the melt surface (argon protecting atmosphere) were applied. As charge materials, technically pure metals, ferroalloys and master alloys were used.

The applied metallurgical treatments (deoxidation, pressure reduction, argon protection) reduced the severity of casting defects due to a very high reactivity of molten nickel alloy with the atmosphere of furnace chamber and the ceramic material of crucible and mould. The pouring temperature did not exceed 1600°C. Table 1 shows the chemical composition of the resulting test melt.

Table 1. Chemical compositions of Inconel 740 made by the Foundry Research Institute and according to literature data

Source	Content of elements; wt.%										
	C	**Cr**	**Mo**	**Co**	**Al**	**Ti**	**Nb**	**Mn**	**Si**	**Fe**	**Ni**
Experiment [1)]	0,10	25,0	0,40	20,0	0,70	1,80	1,60	0,25	0,57	2,50	rest
Commercial [2)]	0,03	25,0	0,50	20,0	0,90	1,80	2,00	0,30	0,50	0,70	rest
Literature [3)]	0,032 0,074	23,0 25,3	0,40 0,59	19,27 19,91	0,70 0,84	1,69 2,00	1,87 2,05	0,28 0,30	0,47 0,52	0,7 2,1	rest

[1)] melt made at the Foundry Research Institute,

[2)] leaflet published by Special Metals,

[3)] B. A. Baker, G. D. Smith: Corrosion Resistance of Alloy 740 as Superheater Tubing in Coal-Fired Ultra-Supercritical Boilers, Special Metals Corporation.

After melting, test moulds were poured with the examined alloy and during its solidification the thermal analysis was carried out.

The results of the thermal analysis of the solidifying Inconel 740 alloy are shown in Figure 2. They are helpful in selecting the heat treatment parameters.

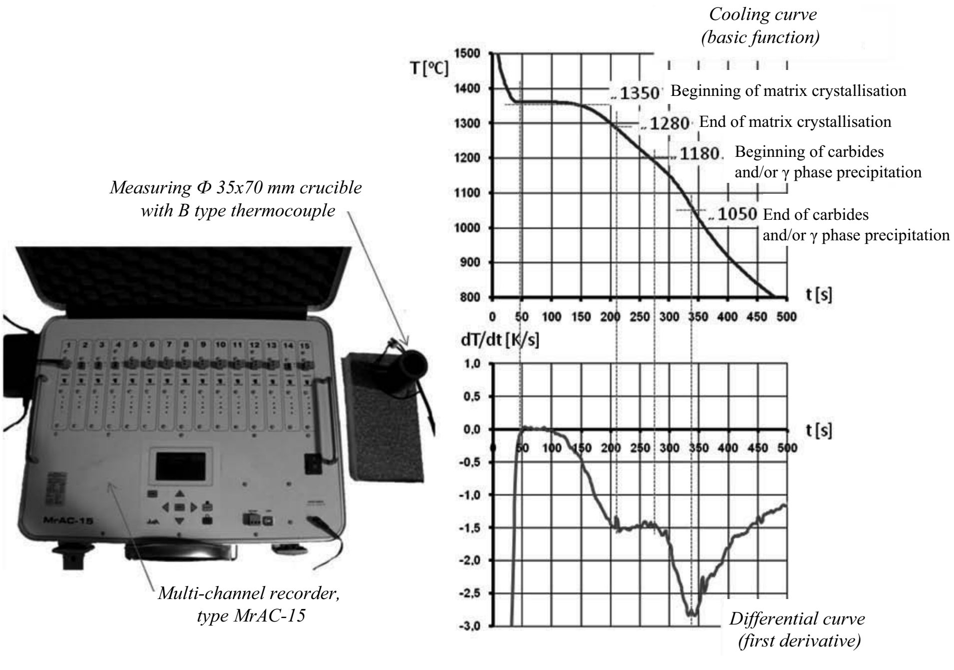


Fig. 2. Thermal analysis of the solidifying Inconel 740 alloy

The cast Inconel 740 alloy has been subjected to materials testing. To perform the tests it was necessary to first select the time and temperature parameters of the heat treatment process.

After the metallographic examinations and hardness and microhardness testing (tests were performed on alloy after different variants of heat treatment), it was decided that the best, in terms of the required properties, heat treatment process would be that depicted in Figure 3. Consequently, before mechanical tests, samples were subjected to this heat treatment.

The applied metallurgical treatments reduced only the severity of internal defects in the cast alloy. To minimise their impact on the results of the tests and examinations, samples were subjected to non-destructive testing, first, and selected for further studies, next. Based on the results of the X-ray examinations, places in the samples with no apparent discontinuities were found. Despite this, in some specimens after rupture, the defects still appeared. Other samples were examined by tomography on CT computers of two types (Figure 4).

Microstructure of *Inconel* 740 *alloy*
Sample „C”
Solutioning: 1200°C/3h/air
Aging: 850°C/16h/air

- two-phase matrix within the whole alloy volume,
- comparable fraction of individual phases in matrix suggests the occurrence of γ/γ' type eutectic

Fig. 3. Microstructure of specimen „C”

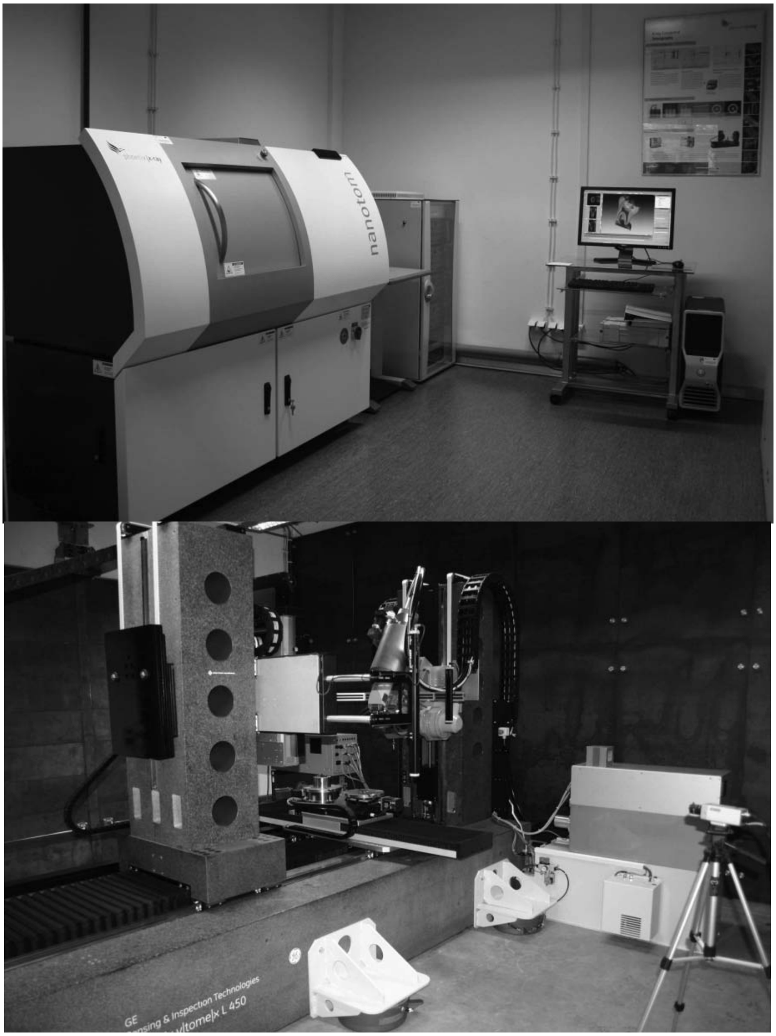
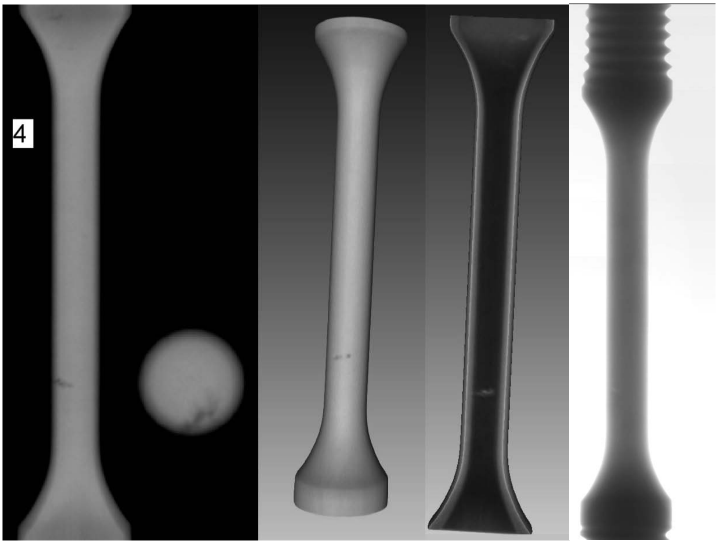


Fig. 4. Nanotom 180 NF (left) and V│Tome│X – L 450 (right)

The tomography done with Nanotom 180 NF (maximum voltage on tube - 180 kV) revealed no internal defects. The reason was that the radiation emitted by the tube was absorbed by the tested material to the extent that made the assessment of internal metal structure impossible. However, the examinations done with tomograph V │ Tome │ X - L 450 (maximum voltage on tube - 450 kV) revealed the presence of internal discontinuities in the examined sample material. For mechanical testing, samples with the least visible internal defects were selected (Figure 5).



X-ray image after visualisation after reconstruction

Fig. 5. Examples of the results of non-destructive testing with V | Tome | X – L 450 tomograph (possible occurrence of minor material discontinuities in the lower part of specimen)

The selected samples were subjected to high-temperature mechanical testing. Analysis of the obtained results (Figure 6) shows that, under the conditions of the Foundry Research Institute in Cracow, the production of nickel superalloys characterised by satisfactory high-temperature properties is quite feasible.

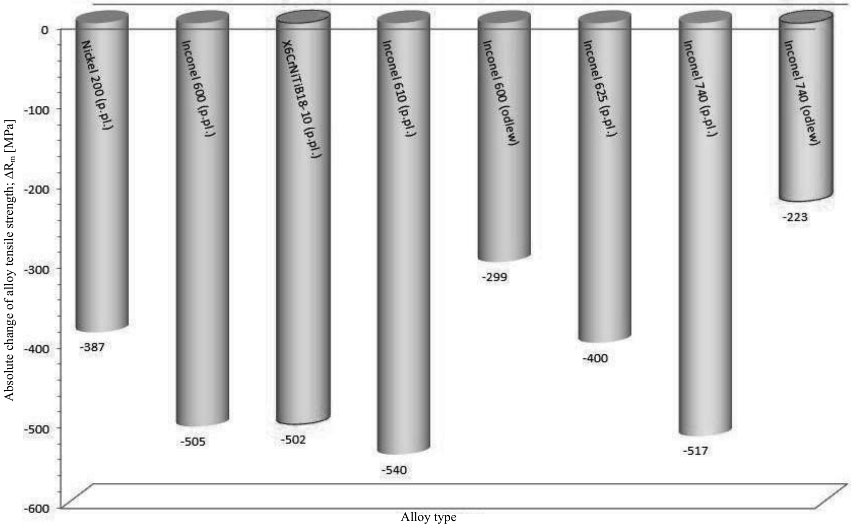


Fig. 6. Changes of tensile strength in selected alloys within the temperature range of 20-800°C
p.pl. – wrought, odlew - cast

Obtained at different temperatures (20°C, 500°C, 700°C and 800°C) results of the tensile test and their comparison with literature data show that cast Inconel 740 (own research) and Inconel 600 (literature data) have lower tensile strength than their wrought counterparts, but with increased temperature of measurement the drop in the value of this parameter is less drastic in cast alloys. This becomes particularly evident at a temperature above 700°C due to loss of the work hardening effect.

Among the comparable alloys, with temperature increasing in the range of 20-800°C, the least drastic decrease in tensile strength revealed the, cast at the Foundry Research Institute, Inconel 740 alloy (ΔR_m = - 223 MPa), while for wrought Inconel 740 alloy (literature data), this difference was ΔR_m = - 517 MPa.

Hence the conclusion follows that by replacing wrought alloys with cast nickel superalloys in structures operating at extra high temperatures, the weight of these elements can be effectively reduced.

CONCLUSIONS

1. The conducted heat treatment (solutioning and aging) had a significant effect on microstructure of the tested *Inconel 740* alloy and on hardness and microhardness of the austenitic matrix.
2. The highest degree of hardening, and hence the increase in hardness of *Inconel 740* alloy was obtained by solution heat treatment at 1200°C for 3 h, followed by aging at 850°C for 16 h.
3. The results of tensile testing obtained at different temperatures (20°C, 500°C, 700°C and 800°C), when compared with literature data, have proved that cast *Inconel 740* and *Inconel 600* alloys have lower tensile strength than alloys after plastic forming, but with increasing temperature of measurement the drop in the value of this parameter is less drastic in alloys cast. This becomes particularly evident at a temperature above 700 °C.
4. Among the compared alloys, with temperature increasing in a range of 20 - 800°C, the mildest decrease in tensile strength had the, made at the Foundry Research Institute, cast alloy (ΔR_m = - 223 MPa), whereas for wrought Inconel 740 alloy (literature data) this difference was R_m = - 517 MPa.
5. The use of parts cast from nickel superalloys for extra high temperature performance instead of wrought alloy structures can reduce the weight of the elements and increase their service life.

REFERENCES

1. Z. Pirowski: Nikiel i jego stopy specjalnego przeznaczenia; monografia; Instytut Odlewnictwa; in print.
2. B. A. Baker, G. D. Smith: Corrsion Resistance of Alloy 740 as Superheater Tubing in Coal-Fired Ultra-Supercritical Boilers, Special Metals Corporation.
3. E. Rusin: Dobór parametrów obróbki cieplnej nadstopu niklu typu Inconel 740 w celu uzyskania odpowiedniej morfologii wydzieleń dyspersyjnych; Uniwersytet Pedagogiczny; Kraków 2010; praca magisterska realizowana w Instytucie Odlewnictwa.
4. M. Blicharski: Inżynieria materiałowa – stal; WNT; Warszawa 2004.
5. K. Przybyłowicz: Metaloznawstwo; WNT; Warszawa 2007.

6. Z. Pirowski: Zwiększenie odporności na zużycie erozyjne dwufazowego staliwa Cr-Ni przez dodatek azotu i innych pierwiastków międzywęzłowych; Archiwum Technologii Maszyn i Automatyzacji. Komisja Budowy Maszyn PAN Oddział w Poznaniu; vol. 26; nr 1; s. 1005-121; Poznań 2008.
7. Z. Stefański, Z Pirowski i inni: Próby technologiczne wykonywania odlewów ze stopów niklu; Praca statutowa Instytutu Odlewnictwa; Zlec. 3671/00; Kraków 1995.
8. J. M. Svoboda: Nickel and Nickel Alloys; ASM Handbook - Casting; vol. 15; 10th Edition; ASM Metals Park; Ohio 1993; pp. 815-823.
9. L. L. Faulkner: Nickel Alloys; Edited by Ulrich Heubner; Marcel Dekker Inc.; New York – Basel 1998.
10. Stainless Steel World. Internet materials: http://www.stainless-steel-world.net/pdf/11022.pdf.
11. A. Onoszko, K. Kubiak, J. Sieniawski: Turbine blades of the single crystal nickel based CMSX-6 superalloy; Journal of Achievements in Materials and Manufacturing Engineering; vol. 32, 2009; pp. 66-69.
12. L.A. Dobrzański: Materiały metalowe. Stopy niklu i kobaltu; IMIiB; Gliwice 2007.
13. J. Ericsson i inni: High – Temperature Materials in Gas Turbines,; Elsevier SC. Public. Comp.; Amsterdam 1974; s. 315-340.
14. L. Swadźba, M. Śnieżek i inni: Żarowytrzymałe stopy, obróbka cieplna oraz powłoki ochronne stosowane na elementy turbin gazowych; SECO/WARWICK; VII Seminarium Szkoleniowe „Nowoczesne trendy w obróbce cieplnej”; Świebodzin 3003.
15. Advanced Materials and Coatings for Combustion Turbines; Ed. V. P. Swaminathan and N. S. Cheruwu; Prop. of ASM 1993 Materials Congress, Materials Week’93; Pitsburg 1993.
16. Pirowski Z., Gościański M.: Construction and technology of production of casted shared for rotating and field ploughs: TEKA Commission of Motorization and Power Industry in Agriculture Lublin University of Technology the Volodymir Dahl East-Ukrainian National University of Ługańsk: 2009; v. IX; s. 231-239.
17. Bibus Metals; Oferta handlowa; Internet materials: http://www.bibusmetals.pl/?k=strony_p&m=78&ns=19&pns=19.
18. High-temperature, high-strength. Nickel base alloys; Nickel Development Institute; 1995 Suplement; N° 393; Internet materials: http://www.stainless-steel-world.net/pdf/393.pdf.
19. Special Metals Corporation, Huntington, West Virginia, USA; Oferta handlowa; Internet materials: http://www.specialmetals.com/products/index.php.
20. CASTI Metals Red Book. Nonferrous Metals; Fourth Edition; CASTI Publishing Inc.; Edmonton 2003.
21. Stainless Foundry & Engineering, Inc.; Oferta handlowa; Internet materials: http://www.stainlessfoundry.com.
22. Gina Advanced Materials Co., Ltd; Oferta handlowa; Internet materials: http://www.gina.com.cn/en/pro/en_pro1_3.asp.
23. F. R. N. Nabarro, H. L. de Villiers: The Physics of creep; CRC Press; 1995.
24. J. R. Davis: ASM Specialty Handbook: nickel, cobalt and their alloys; ASM International 2000.
25. M. J. Luton: Abstract of Conference High Temperature Alloys for Gas Turbines; Liege 1986.

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ZASTOSOWANIE NADSTOPÓW NIKLU NA ODLEWY ELEMEN-TÓW KONWENCJONALNYCH URZĄDZEŃ ENERGETYCZNYCH

Streszczenie. Elementem mogącym łagodzić skutki różnych kryzysów energetycznych jest ciągłe zwiększanie sprawności urządzeń energetycznych. Można to uzyskać prowadząc pro-cesy technologiczne w coraz wyższej temperaturze, ciśnieniu i agresywniejszym środowisku niż stosowane dotychczas. Takim wymogom nie mogą sprostać już stopy na bazie żelaza, na-wet najlepsze z nich pod tym względem. Sięga się tu po wieloskładnikowe stopy na bazie niklu i kobaltu. Powstają wciąż nowe tworzywa o coraz większej trwałości eksploatacyjnej.

Instytut Odlewnictwa w Krakowie wspólnie z partnerami amerykańskimi prowadzi pra-ce badawcze, których celem jest między innymi dokonanie konwersji materiałowej i techno-logicznej konstrukcji kuto-spawanych wykonywanych z nadstopów niklu, na elementy odle-wane z przeznaczeniem do pracy w najtrudniejszych warunkach eksploatacyjnych urządzeń energetycznych nowej generacji. Jest ona realizowana między innymi w ramach amerykań-skiego programu „A-USC – NICKEL”, do prac, w którym został zaproszony Instytut Od-lewnictwa. W ramach tych prac wykonano już wstępne badania polegające na opanowaniu techniki topienia i odlewania stopu Inconel 740 oraz przeprowadzono wstępne badania mate-riałowe wykonanych odlewów. Stwierdzono między innymi, że ze wzrostem temperatury, zwłaszcza powyżej 700 oC, stop ten, jako stop odlewniczy wykazuje zdecydowanie mniejszy spadek wytrzymałości na rozciąganie niż analogiczny stop przerabiany plastycznie.

Słowa kluczowe: odlewnicze nadstopy niklu, technologia wytwarzania, właściwości mecha-niczne, mikrostruktura, umocnienie dyspersyjne.