THE APPLICATION OF HOT ISOSTATIC PRESSING PROCESS TO REJUVENATE SERVICED CAST SUPERALLOY TURBINE BLADES

Wangyao P.[1], *Polsilapa S.*[2], *Nisaratanaporn E.*[3]
[1] *Metallurgy and Materials Science Research Institute (MMRI), Chulalongkorn University, Bangkok, Thailand*
[2] *Dept. of Materials Engineering, Engineering Faculty, Kasetsart University, Bangkok, Thailand*
[3] *Dept. of Metallurgical Engineering, Engineering Faculty, Chulalongkorn University, Bangkok, Thailand*

VYUŽITIE PROCESU IZOSTATICKÉHO LISOVANIA ZA TEPLA NA ZOTAVENIE PREVÁDZKOVANEJ ODLIEVANEJ TURBÍNOVEJ LOPATKY ZO SUPERZLIATINY

Wangyao P.[1], *Polsilapa S.*[2], *Nisaratanaporn E.*[3]
[1] *Metallurgy and Materials Science Research Institute (MMRI), Chulalongkorn University, Bangkok, Thailand*
[2] *Dept. of Materials Engineering, Engineering Faculty, Kasetsart University, Bangkok, Thailand*
[3] *Dept. of Metallurgical Engineering, Engineering Faculty, Chulalongkorn University, Bangkok, Thailand*

Abstrakt

Predkladaný príspevok je pokusom získať vhodnejšie a praktickejšie podmienky obnovy mikroštruktúry dlhodobo exponovaných lopatiek plynovej turbíny z odlievanej niklovej superzliatiny IN-738, ktoré boli prevádzkované spoločnosťou Electricity Generating Authority of Thailand (EGAT). Použitou metódou na zotavenie štruktúry a zabezpečenie optimálnych mikroštruktúrnych charakteristík bol proces izostatického lisovania za tepla (HIP), za ktorým nasledovalo štandartné tepelné spracovanie. Izostatickým lisovaním za tepla je možné odstrániť niektoré vnútorné póry a trhliny (pomocou spekania), ktoré sa vytvorili počas prevádzky. Bolo zistené, že po dlhom čase procesu izostatického lisovania za tepla (3 -4 hodín), nebola pozorovaná v štruktúre materiálu žiadna mikrotrhlina. Okrem toho, vyššia teplota alebo dlhší čas procesu izostatického lisovania za tepla, zabezpečila vyššiu účinnosť uzavretia mikropórov a zníženia porozity materiálu. Hoci je nutné podotknúť, že mikropóry boli pozorované dokonca aj po 4 hodinách procesu izostatického lisovania za tepla pri teplote 1200°C, ale vo veľmi malom množstve. Preto je potrebné študovať veľkosť a množstvo zvyškových mikropórov tak získaného originálneho materiálu ako aj materiálu po dlhom čase prevádzkovania. Okrem toho, počas tepelného spracovania, hrubé karbidy a primárne precipitáty gamma, ktoré sa vytvorili počas prevádzky na hraniciach zŕn creepovým mechanizmom sa môžu rozpustiť v matrici materiálu. Následne boli vzorky spracované sériou procesov starnutia, pri ktorých opätovne vyprecipitovala spevňujúca fáza majúca požadovanú veľkosť, tvar ako aj rozloženie, takmer rovnaké ako mala pôvodná vzorka. Na kontrolu odstránenia mikrodefektov z mikroštruktúry materiálu po procese izostatického lisovania za tepla a následného tepelného spracovania bola využitá optická mikroskopia a riadkovacia elektrónová mikroskopia.

Abstract

The present work has an attempt to possibly obtain the most suitable and practicable repair-condition, which could provide the optimal microstructural characteristics by rejuvenation method of hot isostatic pressing (HIP) followed by standard heat treatment for long-term serviced gas turbine blades, a casting nickel base superalloy grade IN-738 operated by Electricity Generating Authority of Thailand (EGAT). The hot isostatic pressing could mostly heal any internal structural voids and cracks (by means of sintering), which were generated during service by creep mechanism. It was found that no any microcrack was observed after longer times of HIP process such as for 3 - 4 hrs. HIP time period. Furthermore, the higher of HIP temperature and/or the longer of HIP time provided the higher of efficiency for microvoid or porosity closing. However, microvoids were still found even after 4 hrs.-HIP process at 1200°C but in very small amount. Therefore, both size and amount of remain microvoids should be considered comparing to both obtained original material and after long-term service one. Furthermore, during solution treatment, coarse carbides and over-exposed gamma prime precipitates, which formed previously at the grain boundaries during service, would dissolve into the matrix. Then specimens will be processed through a series of precipitation aging, which re-precipitates the strengthening phase to form the proper morphology in size and shape as well as distribution that is almost similar to the new one. Metallurgical examination of the microstructure had been performed by utilizing optical microscope and scanning electron microscope after hot isostatic pressing and heat treatment to evaluate the micro-defects elimination.

Keywords: Hot Isostatic Pressing (HIP), Rejuvenation, Microstructural Repair, Nickel - Based Superalloy

Introduction

This paper presents an applied pilot research and development, which is possible to be done in Thailand for rejuvenation of superalloy components for land-based gas turbine industry especially electricity power plants in Thailand. The increasing of usage and success of the gas turbine power-generation industry in Thailand is strongly dependent on the demands of customers and operators and by arising from a number of market and legislative factors such as capital costs, operational costs, efficiency, power output, fuels, emission (to environment) and so on. Therefore, the operators or electricity generating producers with their own maintenance and repairing, also need a wide range of materials engineering knowledge and skills to ensure safety, reliable operation of the engines as well as costs.

Superalloys are widely used as gas turbine components operating at temperatures above 550°C and up to about 1200°C, which include ducts, cases, and liners as well as for major components such as turbine blades, vanes, disks, and combustion cans. Superalloys can be classified in three main groups: 1) Cobalt-base, 2) Nickel-base and 3) Iron-base superalloys. However, Nickel-Iron-base superalloys are considered as a special group within the nickel-base group. It should be noted that Chromium and Titanium alloys are not regarded as superalloys. Superalloys are now used in aircraft, marine, industrial and vehicular gas turbines, space vehicles, rocket engines, experimental aircraft, nuclear reactors, submarines, steam power plants, petrochemical equipments, and other high-temperature applications. The largest use of superalloys in the present days is the gas turbine industry for aircrafts and power plants [1 - 5]. In contemporary engines, nickel-base alloys are used as dynamic turbine blades, nickel- or nickel-iron-base alloys as turbine wheels and nickel or cobalt-base alloys as vane and combustion cans.

Superalloys, which can be used to withstand high stress (load) at elevated temperatures, generally consist of high creep resistance, high temperature fatigue resistance (both low and high cycles), good thermal fatigue resistance (low thermal expansion and high thermal conductivity) as well as high strength and ductility. Their microstructures and mechanical properties should be stable during operating at high temperatures for long-term services. Furthermore, they should resist surface degradation by hot oxidation and hot corrosion. The other minor requirements are good weldability and formability (in case of wrought polycrystalline alloys). Table 1 reviews briefly the role of various alloying elements play in strengthening conventional nickel-base alloys.

Table 1 Role of alloying elements on nickel-base alloys

Effects	Elements
- Solid solution strengtheners	Co, Cr, Fe, Mo, W, Ta
- Carbide form:	
- MC type	W, Ta, Ti, Mo, Nb
- M_7C_3type	Cr
- $M_{23}C_6$type	Cr, Mo, W
- M_6C type	Mo, W
- Carbonitrides: M (CN) type	C, N
- Oxidation resistance	Al, Cr
- Hot corrosion resistance improvement	La, Th
- Sulfidation resistance	Cr
- Improves creep properties	B
- Increase rupture strength	B
- Causes grain boundary segregation	B, C, Cr

The individual phases in the microstructure of superalloys have tendency to transform toward equilibrium when exposed to high temperatures. Many phase changes could occur depending on the temperature levels and time of exposure. Unfortunately, phase instability results in weaken- or brittle- phase formation presence in some alloys. Nickel is excellent base metal when it is highly alloyed. It has stronger tolerance for alloying additions without any detrimental phase formation. Furthermore, after long-term exposed services without or with applied load (especially under creep condition, which is the most regarded as widely operated condition), precipitates could become coarsening and coalescence, which could be followed by void formation on grain boundaries [1 - 8].

Such kind of degraded microstructure would then theoretically provide worse mechanical properties at elevated temperatures resulting in a decrease of lifetime services. Not only phase changes occurring under applied load at high temperature conditions, microvoids or creep cavitations as well as microcracks could appear intergranularly and/or transgranularly in the alloys causing the following nucleation and propagation of macroscopic fracture. Therefore, the main concept for material repair routes is to eliminate the creep damage by closing microvoids or microcracks including restoring the alloy microstructure by hot isostatic pressing and rejuvenation heat treatment processes to reach the new material properties (especially creep strength) [2 - 11].

Moreover, mechanical damage of the superalloy blades or vanes could occur from foreign object damage, rubs, erosion, and burning. Depending on the location and severity of the damage, the repairs can be completed by process such as blending, precision welding, plasma spray, or powder metallurgy (PM). Any type of these macroscopic damages must be repaired before the alloy microstructure and mechanical properties of the alloy component being restored. Due to its high production cost from complex process conditions and expensive alloying elements being used, the service life extension of gas turbine components is becoming increasing important in the current days. Therefore, it is very important to establish the methodology of rejuvenation for cast superalloy components after long-term services at high temperatures causing microstructural degradation as well as creep damage. In the case of conventionally polycrystalline cast superalloys, the creep damage occurs firstly as the microstructure changes such as coarsening and coalescence of γ' and/or other precipitates, which is followed by void formation at grain boundaries.

Rejuvenation heat treatment processes

Vacuum heat treatment is widely used during the repair process for many reasons such as improving weldability, stress relieving in welds, coating diffusion and restoring alloy microstructure. In a vacuum furnace, the alloy blades or vanes are held at the solution temperature, which causes the coarse carbides, gamma prime and gamma double prime, being formed in the grain boundaries during service, to be dissolved into the matrix, see Fig. 1. The turbine blades or vanes are then processed through a series of aging cycles, which re-precipitate the strengthening phase to form microstructure similar to a new part. Although the perfect microstructure recovery is not always possible due to the presence of grain boundary strengthening elements, i.e., carbon and boron, which decrease the incipient melting temperatures to prevent perfect solutioning of the gamma prime phase.

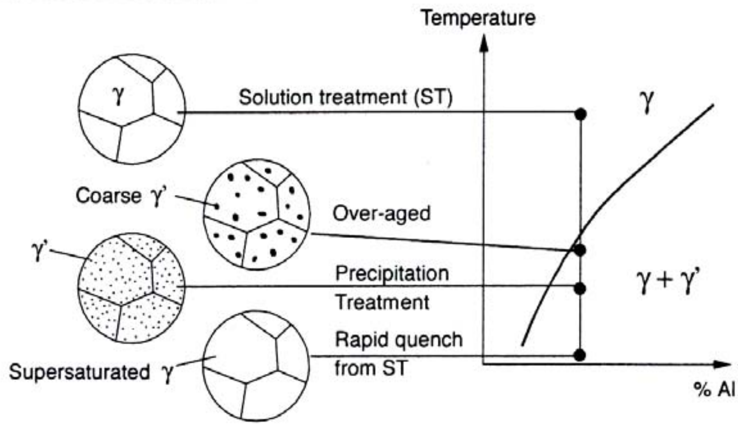

Fig.1 Heat treatment diagram for precipitation strengthening in nickel-base superalloys [8]

Conditions of heat treatment processes were developed especially for rejuvenation of each alloy. However, very few applied research programs [3 - 4] for rejuvenation heat treatment have been developed and carried out in Thailand, which all have the aim to reduce material costs in the gas turbine industry. During the repairing process for components, sample material should be subjected to the same heat treatment and subsequently receive qualification tests such as microstructural examination as well as mechanical tests (hardness, tensile tests at elevated temperatures including creep and/or stress rupture tests to ensure rejuvenated materials meeting the original new material specification.

IN-738, a cast nickel based superalloy was originally developed as a material for turbine blade applications. It was specially designed for long-term service in excess of 100,000 hours at temperature up to 980°C with surface coating. Its chemical composition was developed to obtain an excellent combination between mechanical and physical properties such as high temperature tensile and fatigue strength, creep strength, fracture toughness, thermal fatigue, structural stability including hot corrosion and hot oxidation resistance. Optimum creep properties, a major concerned application, were achieved by solid solution strengthening in matrix, precipitation strengthening by γ' phase and partially obtaining from carbide phase strengthening, which all are followed by heat treatment process (solutioning treatment and precipitate aging). The mechanical properties at elevated temperature in superalloys relate strongly to its microstructure [12 - 20]. The IN-738 material is used as a material for gas turbine in power plant of Electricity Generating Authority of Thailand in a present day.

It is very necessary to determine methods providing proper microstructural characteristic restoration of the material after long-term usage. The method should also prevent or prolong the service time before the creep damages occur. However, the complete microstructure recovery is not always possible due to the presence of grain boundary strengthening element, i.e. carbon, which decreases the incipient melting temperatures preventing the complete solution of carbide phase. Thus, microstructural degradation before creep damage in cast polycrystalline nickel-base superalloy, IN-738, can be expected to be almost eliminated by a simple re-heat treatment to restore the proper microstructure for good creep resistance resulting in longer lifetime services of the material. In the present study, the effect of re-heat treatment conditions on the microstructural characteristics of nickel base superalloy was examined for the microstructure recovery and the creep lifetime extension.

The service lifetime extension of gas turbine components is becoming increasingly important, especially with nickel-base superalloy turbine blades and vanes. At present, their production-costs are becoming much higher due to the complex process conditions and expensive alloying elements. In the case of conventional casting superalloys, the creep damage occurs firstly as the microstructure changes such as coarsening and coalescence of gamma prime precipitates, which is then followed by void formations typically showing up at grain boundaries. Thus, a classical hot isostatic pressing process is required to eliminate the creep damages [2, 6, 21].

Hot isostatic pressing process offers the possibility of eliminating closed porosity, voids and creep voids in cast components. HIP process is able also to improve the homogeneity of the microstructure, both by dissolution of segregates and by elimination of porosity, as well as the material properties. This is especially important in the case of cast parts, which are subjected to very high stresses, such as turbine blades made of nickel base superalloys. Turbine blades for aircrafts and stationary gas turbines are among the first applications of HIP process to cast products [6, 9, 22 - 23]. Furthermore, HIP process is also utilized for both improvement of weld or braze material (porosity removal and improved bonding) and for the removal of creep porosity development during previous service in the area of turbine blade rejuvenation.

The blades or vanes are processed at solution temperature under very high pressures in an inert gas environment. The process could heal any internal structural voids or porosity and prepare the material for heat treatments. In a furnace, the blades or vanes are held at the solution temperature, which causes the coarse carbides, gamma prime, and gamma double prime, be formed at grain boundaries during service, and be dissolved in the matrix.

According to previous work [9], the rejuvenation process provides blades to double and in some cases, triple the lifetime as compared to the original ones. For alloys such as IN 738, IN 792, U 500, X-750 and the newer alloys such as GTD 111, GTD 111DS, R80DS, and IN 939, which are used in many landed-base gas turbines, have been rejuvenated and successfully returned to service according to the previous information of LIBURDI Engineering

Company Limited, Canada. In each case, the blades were creep life expiry when received for processing and then giving reliable service after rejuvenation.

Experimental Material and Procedures

The aim of this research work is to determine the most suitable and practicable repair-condition, which provides the best microstructural characteristics by rejuvenation method of hot isostatic pressing followed by standard heat treatment for long term exposed gas turbine blades, casting nickel base superalloy grade IN-738 (see chemical composition in Table 2), after 70,000 hours service operated by Electricity Generating of Thailand (EGAT). HIP conditions are illustrated in Table 3, and then the best HIPed specimen was heat treated in standard condition (1125ºC/2 hrs. (AC) + 845°C/24 hrs. (AC)). The size of closing voids and/or microcracks was investigated by scanning electron microscope (SEM).

Table 2 Chemical composition of IN-738 (in weight %)

Ni	Cr	Co	Ti	Al	W	Mo	Ta	Nb	C	Fe	B	Zr
Bal.	15.84	8.5	3.47	3.46	2.48	1.88	1.69	0.92	0.11	0.07	0.12	0.04

Table 3 HIP conditions applied to long-term exposed IN-738

No.	Pressure (MPa)	Temperature (°C)	Time (hrs.)
1	100	1100	1
2	100	1100	2
3	100	1100	3
4	100	1100	4
5	100	1200	1
6	100	1200	2
7	100	1200	3
8	100	1200	4

Results and Discussion

The SEM observation of all specimens after long-term service was supposed to confirm the progress of internal voids, as shown in Figs. 2 - 5. The SEM analysis of un-etched specimens shows the presence of microvoids locating both in the matrix and at the carbides, which had been developed during service under long-term stress and temperature. The diameter size and amount of microvoids depend on the location of turbine blade. It was found that the zone of airfoil tips, upper parts of turbine blade, consist of more amount and bigger diameter size of microvoids. This was because an effect of much higher temperature took place during operation causing the higher rate of diffusion for internal void nucleation and growth.

However, after HIP process in all testing conditions, it should be noted that the HIP parameters such as temperature and time have a great effect on the efficiency of internal void sintering, see Fig. 6. The process temperatures were selected so that the alloy yielded or crept in compression under the action of the applied pressure. The result is elimination of internal voids (porosity) and/or microcracks as well as nearly full densification of the alloy. HIP is able to almost remove internal voids and promote diffusion bonding across the surfaces of the void, which is replaced by continually sintered material. Higher temperature and longer HIP time show the smaller internal void diameter. As it was already known that higher temperature and longer time during HIP process provides the significant beneficial effect in sintering process. The role of applied temperature and time is to increase the opportunity for diffusion rate and diffusion time to take place across the interface for local yielding and creep, which can increase the real area of contact. Nevertheless, the information from the result of Fig. 6 is probably not enough to indicate that these HIP conditions are not proper to close all microvoids completely. It should be noted that not only the reduced microvoid diameters, which should be counted but also the amount of remain microvoids. It was found that the amount of remain microvoids decreased drastically when HIP time was increased. Therefore, by SEM investigation in specimens according to programs No. 7 and 8, it was still found the few microvoids but they were very rarely to be detected. This fact is very important to consider about the advantage of HIP process for refurbishment of superalloy components.

Furthermore, the amount of internal voids (micro-voids, see Figs. 7 and 8) is also dependently decreased by an increase in HIP temperature and time. However, from Fig. 6, it should be noted that the internal void closing rate at earlier stage (0 - 1 hr.) is a bit faster than that of the middle (1 - 2 hrs.) stage. The last (3 - 4 hrs.) stage has the rate of internal void closing a bit slower than that of the middle one. This seems that the efficiency of HIP process to close internal void slightly decreased when the period of HIP time increased continuously. Followed by standard heat treatment after HIP program of No. 8, it was found by SEM investigation that the microstructural homogeneity is clearly increased, Figs. 9 and 10. It can be seen by comparing the size and morphology of gamma prime between initial state (as-received material after long-term service) and HIPed and then heat-treated state. All significant features in microstructure of all HIPed and heat-treated specimens are theoretically supposed to be the desired microstructure for better creep strength [6].

From previous work [6], which reported that HIP process could provide the narrowing of the scattered band for some properties in IN-738. While minimum fatigue lives are improved by HIP, minimum rupture lives are not always improved. HIP can be considered as a heat treatment and will solution and change γ' in the alloy. The following solution and aging heat treatments are required to develop mechanical properties as desired. Furthermore, if the post-HIP solution treatment is not carried out at a temperature above the HIP temperature, the resulting γ' structure may be not adequate to produce optimal strength. Therefore, this seems that the applied normal standard heat treatment, which consists of solution treatment of 1125°C might not proper to the alloy after HIP process at temperature of 1200°C but this standard heat treatment might only proper to the HIP process of 1100°C.

However, according to the previous study [10, 23], it reports that a long-term service run IN-738 airfoil that processed through the standard heat treatment, the obtained microstructure could be only partially recovered. This study informed that the most suitable γ' solution temperature for IN-738 alloy ranges from 1175 - 1190°C. To fully restore the microstructure after service exposure, these alloys are recommended to be solutioned at 1200°C, which is the same as the HIP temperature of last four programs. As it can be seen, that the HIP temperature of 1200°C is already sufficient to completely solution γ' particles to the microstructure. Therefore, the standard heat treatment is also possible to be used after HIP process at temperature of 1200°C.

Furthermore, according to the other previous works [10, 23] about re-heat treatment of the alloy, it was found that the low solution temperature (1125°C) of standard heat treatment for long-term service IN-738 turbine blade is adequate to dissolve γ' into the matrix and later providing the uniform dispersed γ' precipitation after the following aging step. In addition, from the result in this present study, it can be also confirmed by Fig. 10 that the proper uniform microstructure can be obtained when applied only the standard heat treatment after HIP process at 1200°C for the received certain alloy condition. This can be probably summarized that the level of solution temperature is strongly in dependent with the morphology of precipitated γ' particles of the alloy after long-term service, which the coarser or more rafting γ' precipitates (usually occur at very long-term service under high loading and/or very high temperature service conditions) need higher solution temperature and/or longer solution time. In another hand, the less coarsening or rafting precipitated γ' particles probably required the lower solutioning temperature and/or shorter solution time as in the standard heat treatment.

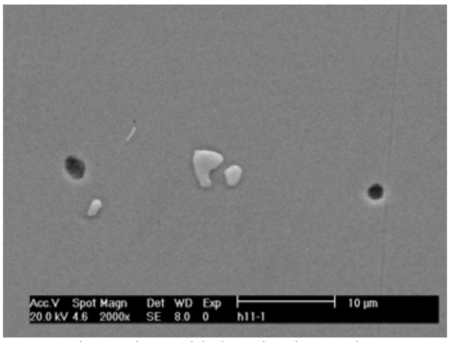

Fig.2 Microvoids locating in matrix

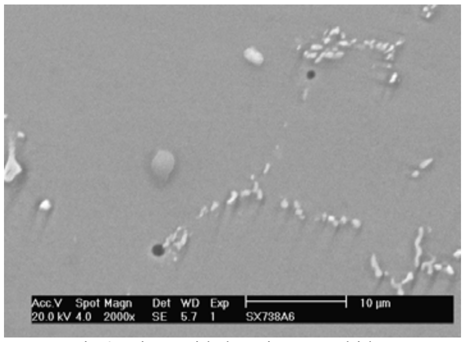

Fig.3 Microvoids locating at carbides

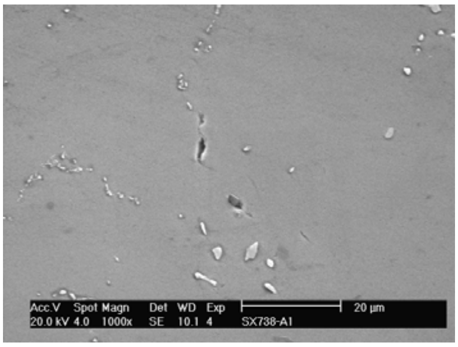

Fig.4 Microcracks locating in matrix

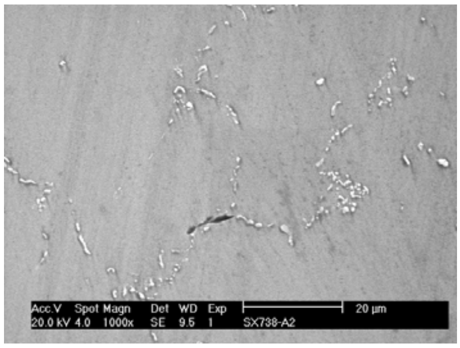

Fig.5 Microcracks locating at carbides

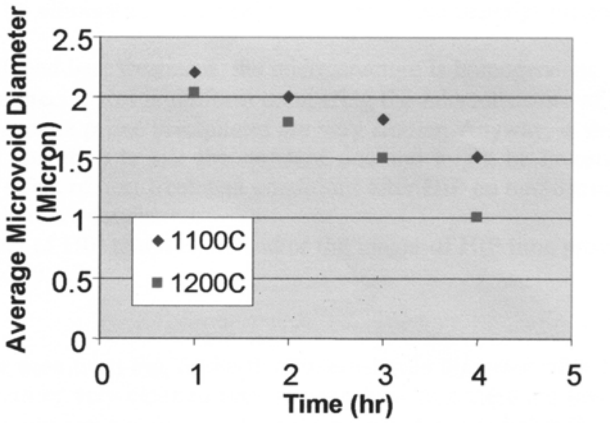

Fig.6 The relationship between internal void diameter and HIP time

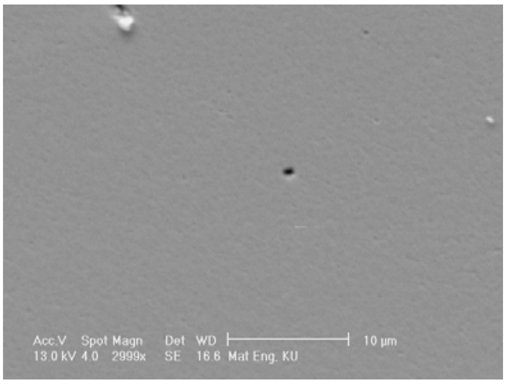

Fig.7 After HIP at 1100°C for 4 hrs.

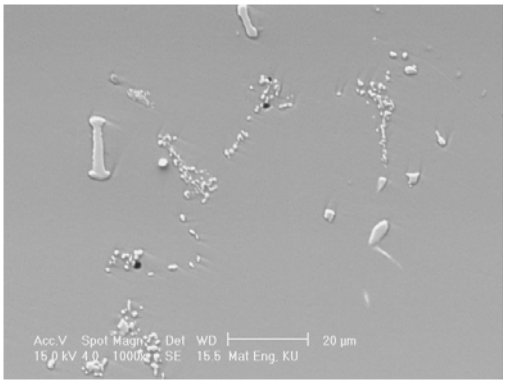

Fig.8 After HIP at 1200°C for 4 hrs.

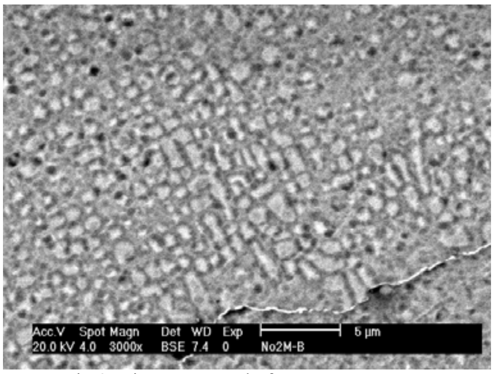

Fig.9 Microstructure before HIP process

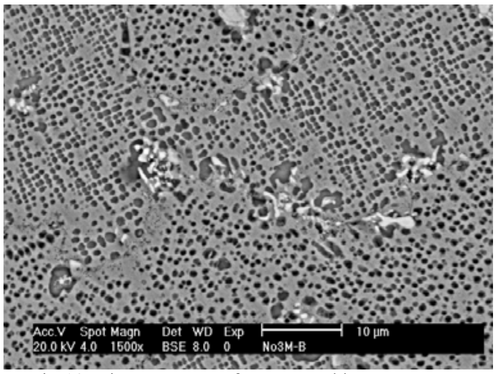

Fig.10 Microstructure after HIP and heat treatment

Conclusions

1) Hot isostatic pressing offers the possibility of eliminating porosity or voids from shrinkage and creep voids in cast components. No microcrack was observed after HIP process. HIP is able also to improve the homogeneity of the microstructure, both by dissolution of segregates and by elimination of porosity, as well as the material properties according to previous work [6].
2) After HIP and heat treatment, the microstructure is homogeneous. The dispersion of finer gamma prime precipitates is uniform comparing the microstructure of exposed material. Size and shape of gamma prime precipitates are very similar. Anyway, it should be noted that the heat treatment condition is just the standard one and might be investigated in the next research about the effect of heat treatment conditions after HIP on microstructural evolution in the future to study in more details.
3) The higher of HIP temperature and/or the longer of HIP time provide the smaller of closed void or porosity.

Future works

As it can be seen from Fig. 8, the final internal void diameter, after HIP at 1200°C for 4 hours, was not zero or very close to zero yet. It means that there are few very small micro voids still found inside the material so it might be recommended that it would be better to continue this HIP research program for longer HIP times such as for 5 and 6 hours and the higher of pressure (such as till 120 - 130 MPa) in the future to completely close any microvoid.

Acknowledgements

This research project was supported by grant of Ratchada Research Fund, Chulalongkorn University, Bangkok, Thailand. Special thank is also extended to Ing. Weerasak Homkajai at EGAT for material and technical supporting. The author also would like to acknowledge to Ing. Jumpot Wanishsamphan and Ing. Srichalai Khunthon at MMRI and other colleagues at EGAT for technical help.

Literature

[1] Sims C. T., Hagel W. C.: The superalloys, John Wiley & Son Inc., 1972
[2] Sims C. T., Boone D. H.: SUPERALLOYS in Heavy - Gas Turbine Engines Vol. I & II, 1995
[3] Sims C. T., Stoloff N. S., Hagel W. C.: SUPERALLOYS II, John Wiley & Son Inc., 1987
[4] Bradley E. F.: Superalloys: A Technical Guide, ASM International, 1989
[5] Davis J. R.: Nickel, Cobalt, and their alloys, ASM Specialty Handbook, ASM International, 2000
[6] Donachie M. J. and Donachie S. J., SUPERALLOYS: A Technical Guide, 2nd edition, ASM International, 2002
[7] Donachie M. J.: Superalloys Source Book, ASM International, 1984
[8] Meetham G. W., Van de Voorde M. H.: Materials for High Temperature Engineering Application, Springer, 2000
[9] http://www.liburdi.com
[10] Daleo J. A., Ellison H. A., Boone D.H.: Journal of Engineering for Gas Turbines and Power, July 2002, Vol. 124, pp. 571 - 579
[11] Tillack D. J., Manning J. M., Hensley J. R.: Heat treating of nickel and nickel alloys in: ASM Handbook, Vol. 4, pp. 907 - 912
[12] Zrník J., Horňak P., Pinke P., Žitňanský M.: Creep Fatigue Characteristics of Single Crystal Nickel Base Superalloy CMSX 3, Metals Alloys Technologies (Kovine zlitine technologije), 3 - 4, Ljubljana, Slovenia, 1996, pp. 179 - 183
[13] Zrník J., Wang J.A., Yu Y., Peijing L., Horňak P.: Influence of cycling frequency on cycling creep characteristics of nickel base single crystal superalloy, Materials Science and Engineering, A234-236, 1997, pp. 884 - 888
[14] Zrník J., Huňady J., Horňak P.: Nickel Based Single Crystal Superalloy CM 186 - potential Material for Blades of Stationary Gas Turbine, Metallurgy, 41, 3, 2002, pp. 232
[15] Zrník J., Strunz P., Horňak P., Vrchovinský V., Wiedenmann: Microstructural changes in long-time thermally exposed Ni-base superalloy studied by SANS, Journal of Appl. Phys. A 74, 2002, S1155 - S1157
[16] Zrník J., Strunz P., Vrchovinský V., Muránsky O., Horňak P., Wiedenmann A.: Creep deformation and microstructural examination of a prior thermally exposed nickel base superalloy, Key Engineering Materials, Vols. 274 - 276, 2004, pp. 925 - 930
[17] Zrník J., Horňak P., Vrchovinský V., Kubík N.: Stabilita štruktúry niklových tvárnených zliatin v podmienkach tepelnej únavy, Acta Metallurgica Slovaca, 3, 1/2, 1997, pp. 186 - 191

[18] Jenčuš P., Zrník J., Lukáš P., Horňak P.: Thermal fatigue aspects in nickel base single crystal superalloy, Acta Metallurgica Slovaca, 10, 2004, pp. 487 - 493
[19] Zrník J., Strunz P., Vrchovinský V., Muránsky O., Horňak P., Wiedenmann A.: Evaluation of structure stability in thermally exposed nickel base superalloy, Acta Metallurgica Slovaca, 10, 2004, pp. 448 - 453
[20] Zrník J., Semeňák J., Horňak P., Vrchovinský V.: Lifetime behaviours of the wrought nickel base superalloy subjected to low cyclic fatigue with holds, Kovové Materiály - Metallic Materials, Vol. 43, No. 1, 2005, pp. 93 - 104
[21] Tien J. K. and Caulfield T.: Superalloys, Supercomposites and Superceramics, Academic Press, INC, 1989
[22] Wangyao P. et al.: Journal of Metals, Materials and Minerals, Vol. 14, No. 1, pp. 89 - 94, 2004
[23] Wangyao P. et al.: Journal of Metals, Materials and Minerals, Vol. 14, No.1, pp. 49 - 59, 2004