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Thermal Analysis in the Technological "Step" Test of H282 Nickel Alloy

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Abstract

Superalloys show a good combination of mechanical strength and resistance to surface degradation under the influence of chemically active environments at high temperature. They are characterized by very high heat and creep resistance. Their main application is in gas turbines, chemical industry, and in all those cases where resistance to creep and the aggressive corrosion environment is required. Modern jet engines could never come into use if not for progress in the development of superalloys. Superalloys are based on iron, nickel and cobalt. The most common and the most interesting group includes superalloys based on nickel. They carry loads at temperatures well in excess of the eighty percent of the melting point. This group includes the H282 alloy, whose nominal chemical composition is as follows (wt%): Ni - base, Fe - max. 1.5%, Al - 1.5% Ti - 2.1%, C - 0.06% Co - 10% Cr - 20% Mo - 8.5%. This study shows the results of thermal analysis of the H282 alloy performed on a cast step block with different wall thickness. Using the results of measurements, changes in the temperature of H282 alloy during its solidification were determined, and the relationship dT / dt = f (t) was derived. The results of the measurements taken at different points in the cast step block allowed identifying a number of thermal characteristics of the investigated alloy and linking the size of the dendrites formed in a metal matrix (DAS) with the thermal effect of solidification. It was found that the time of solidification prolonged from less than ome minute at 10 mm wall thickness to over seven minutes at the wall thickness of 44 mm doubled the value of DAS.

Keywords: Nickel alloys, Superalloys, Technological "step" test, Thermal analysis

1. Introduction

Superalloys are a group of materials that offer a very good combination of mechanical strength and resistance to surface degradation under the influence of chemically active environments at high temperature. They are characterized by very high heat and creep resistance. Their main application is in gas turbines, in chemical industry and in all those cases where resistance to creep and aggressive corrosion environment is required. Modern jet engines could never come into use if not for progress in the development of superalloys.

The concept of "superalloys" refers to certain alloys based on iron, nickel and cobalt. The most common and the most interesting are nickel superalloys. A noteworthy feature of these alloys is that they can successfully operate in load-bearing applications at temperatures exceeding eighty percent of their melting point [1-3]. Studies of nickel alloys have been for many years conducted at the Foundry Research Institute in Cracow within the framework of an international cooperation [9-12]. One of the alloys on which the attention has recently been focused is H282 of the following nominal chemical composition (wt%): Ni - base, Fe - max. 1.5%, Al - 1.5% Ti - 2.1%, C - 0.06% Co - 10% Cr - 20% Mo - 8.5% [4-6].

Because of high temperatures at which they operate, superalloys undergo only solution or dispersion hardening with other phase particles. They cannot be strengthened by increased density of dislocations (work hardening), or by grain refinement. The effect of several elements on solution hardening characteristics is much stronger than of one element, added in an amount equal to the total content of individual elements.

2. Thermal analysis

Using the results of measurements, changes in the temperature of H282 alloy during its solidification were determined, and the relationship dT / dt = f (t) was derived. A comparison of the primary cooling curve with the differential curve, considered the first derivative of the base function, enabled determining the characteristic parameters of the solidification process, i.e. the beginning of solidification, the maximum rate of solidification, and the end of solidification. The method used in the determination of these parameters is shown in Figure 1.

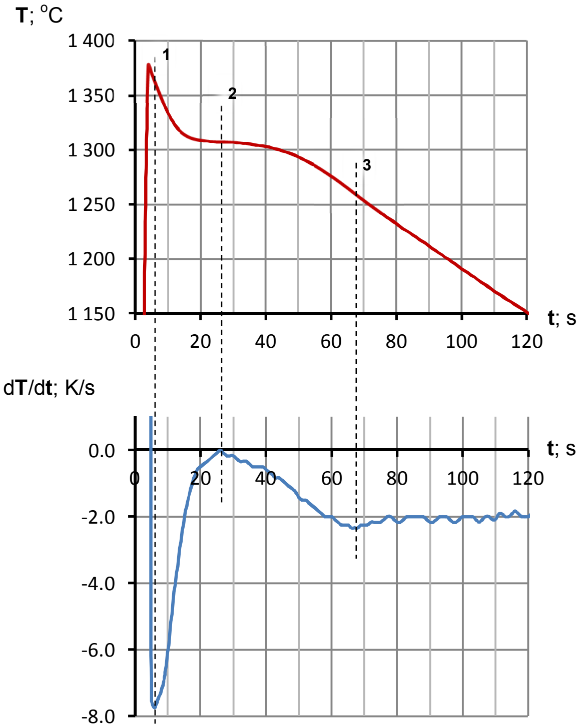

Fig. 1. A method to determine the characteristic parameters of the H282 alloy solidification process: a) base curve T = (t), b) differential curve dT/dt = f (t), where T - temperature, t - time, 1 - the beginning of solidification (t_p), 2 – the maximum rate of solidification, 3 – the end of solidification (t_k)

3. Technological "step" test

Test step blocks are widely used in foundries to describe the effect of casting wall thickness on the alloy solidification process [7, 8].

The tested H282 alloy was cast into sand molds. Molds had a special four-step design. Four thermocouples introduced into the mold cavity and placed at different levels were recording changes in alloy temperature in each of the four steps with different wall thickness. The mold and the method of assembling the thermocouples are shown in Figures 2, 3 and 4. Measurements were taken during the H282 alloy solidification. The alloy originated from two melts designated as H1 and H3. The results of the performed thermal analysis (Figures 5 and 6) show the effect of casting wall thickness on the thermal phenomena taking place in the solidifying metal (H282 alloy).

Fig. 2. A dry two-part mold for the technological "step" test

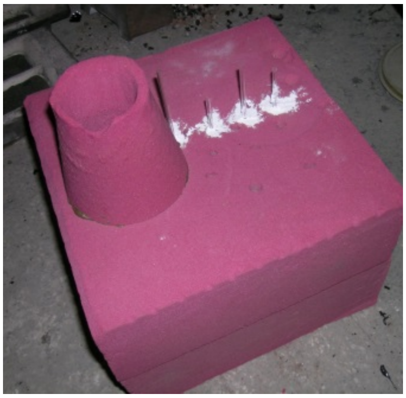

Fig. 3. Ready for pouring and fully equipped mold for the technological "step" test with marked places where four thermocouples were assembled

Fig. 4. Step g x 35 x 150 mm H282 alloy casting used in the conducted tests; g denotes the thickness of each „step"

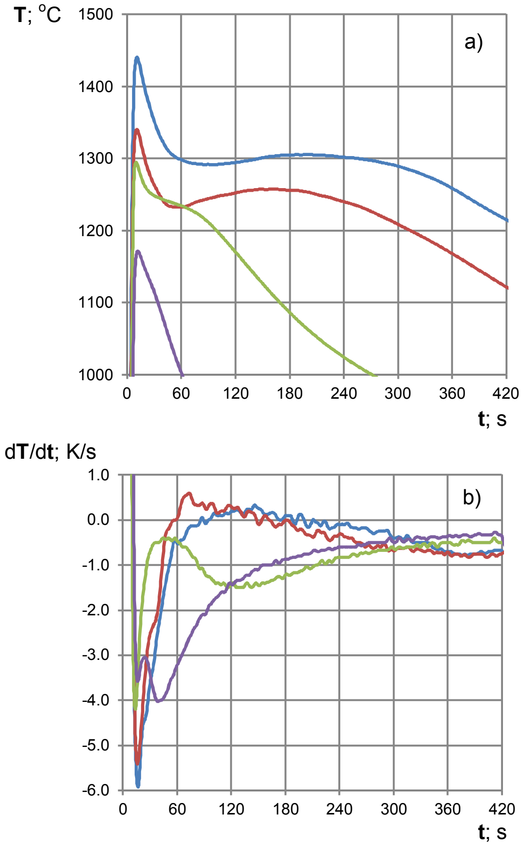

Fig. 5. Cooling curves recorded for the step block cast from melt H1 by four thermocouples placed at different locations in the mold corresponding to four steps with the wall thickness: g1=6 mm, g2=11 mm, g3=23 mm, g4=40 mm;
a) base curve **T** = f(**t**), b) differential curve d**T**/dt = f(**t**).
Violet color represents temperature variations on the cross-section g1, green – on the cross-section g2, red – on the cross-section g3, and blue – on the cross-section g4.

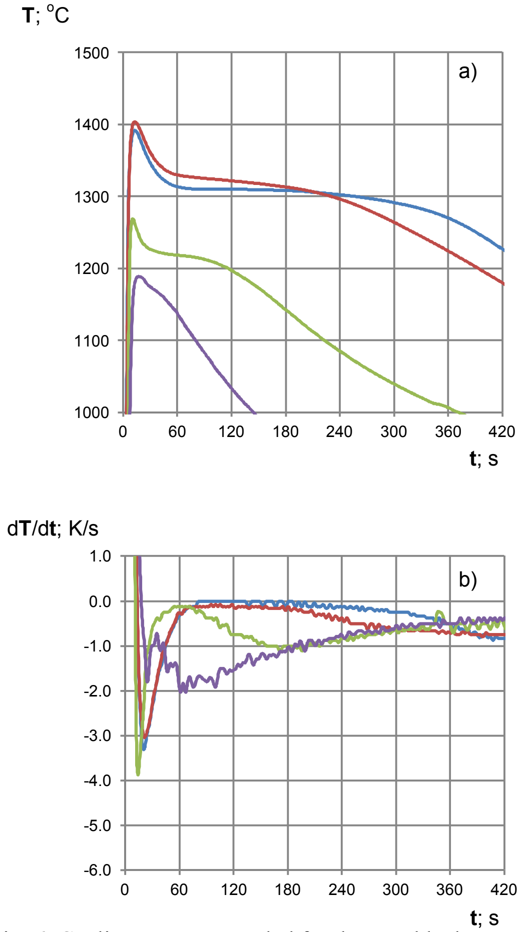

Fig. 6. Cooling curves recorded for the step block cast from melt H3 by four thermocouples placed at different locations in the mold corresponding to four steps with the wall thickness: g1=10 mm, g2=15 mm, g3=28 mm, g4=44 mm;
a) base curve **T** = f(**t**), b) differential curve d**T**/dt = f(**t**).
Violet color represents temperature variations on the cross-section g1, green – on the cross-section g2, red – on the cross-section g3, and blue – on the cross-section g4.

Based on the measured changes in alloy temperature during solidification, recorded at different measuring points, the following thermal characteristics were determined: temperature of the maximum solidification rate, time lapse between mold pouring (the start of recording) and the maximum solidification rate, time lapse between the start and the end of solidification (the solidification time), and the thermal effect of solidification. The measured values of these parameters are given in Table 1, while their dependence on the casting wall thickness is graphically shown in Figures 7-10. The thermal effect of solidification $\boldsymbol{Q}$ was calculated for each of the plotted curves from the following formula:

$$\boldsymbol{Q} = \int_{t_p}^{t_k} \boldsymbol{T} dt \qquad (1)$$

where the limits of integration t_p and t_k are temperatures of the start and the end of solidification, respectively.

Table 1.
The values of thermo-physical parameters of the cast H282 alloy determined from the thermal analysis conducted on a step block

Melting	The thickness of the cast wall [mm]	The temperature of maximum intensity of the solidification [°C]	Time for more intensive solidification [s]	Time of solidicication Δt_{kr} [s]	The thermal effect of crystallization Q [K*s]
H1	6	1140	22	20	23 668
	11	1236	56	111	136 681
	23	1257	146	363	448 354
	40	1306	200	436	561 059
H3	10	1170	34	42	49 984
	15	1217	70	160	193 097
	28	1314	172	364	472 900
	44	1308	208	452	582 662

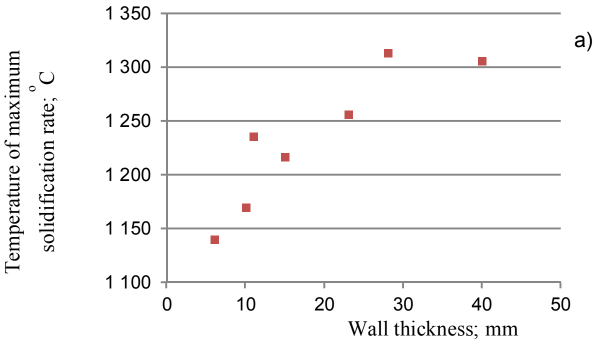

Fig. 7. Temperature of maximum solidification rate as a function of wall thickness in casting made from the H282 alloy (data from melts H1 and H3 were used)

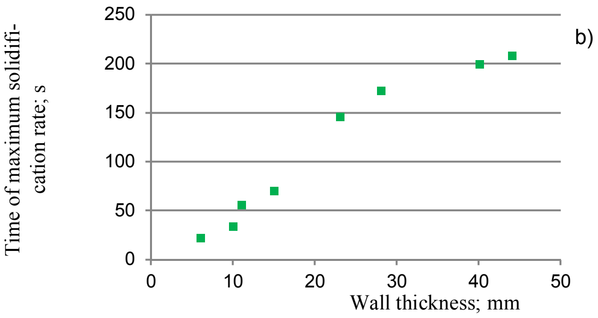

Fig. 8. Time of maximum solidification rate as a function of wall thickness in casting made from the H282 alloy (data from melts H1 and H3 were used)

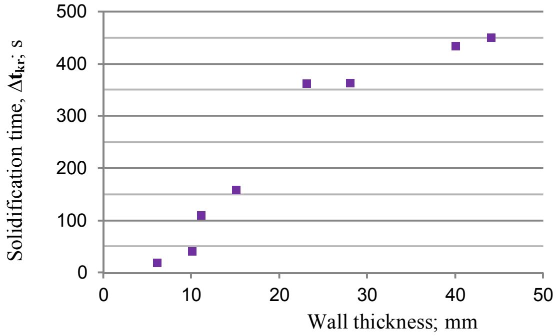

Fig. 9. Solidification time as a function of wall thickness in casting made from the H282 alloy (data from melts H1 and H3 were used)

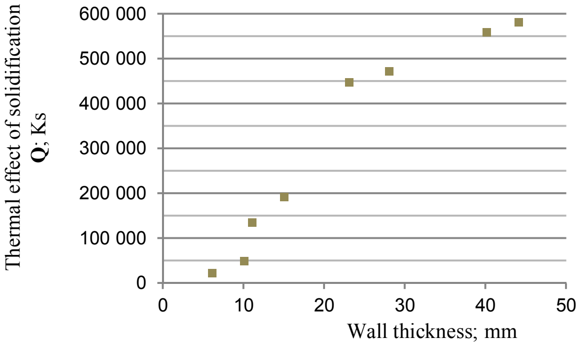

Fig. 10. Thermal effect of solidification as a function of wall thickness in casting made from the H282 alloy (data from melts H1 and H3 were used)

The thermal effect of solidification has a significant influence on structure formation. The sensitivity of H282 alloy to the thermal processes of solidification was determined from the results of metallographic examinations conducted on samples taken from the cast step blocks. The studies enabled evaluation of the size of dendrite arms (DAS) at selected locations in the casting. The measurements were taken on the cross-sections of each step in the test block cast from melt H3. The results show that the values of the DAS parameter significantly increase with the increasing thickness of the casting wall, and therefore with the increasing thermal effect of the solidification process. The average measured values of DAS are in fact 44, 54, 63 and 83 microns for the casting wall thickness of 10, 15, 28 and 44 mm, respectively.

4. Summary and conclusions

Temperature changes taking place in castings, recorded at selected points in the examined step block, enabled a number of thermo-physical parameters to be determined in the solidifying H282 alloy. The values of all thermal characteristics show an increase with the increasing thickness of the cast step wall. The relationship between the thermal effect of solidification Q and the solidification time $\Delta t_{kr} = t_k - t_p$ is of a linear character (Figure 11):

$$\mathbf{Q} = 1276\, \Delta \mathbf{t_{kr}} \quad (2)$$

The empirically determined relationship has the correlation power $r^2 = 0.9986$, and Pearson linear correlation coefficient $r = 0.9993$, and so only 0.14% of the variance Q is accidental, while the remaining 99.86% is associated with a variable $\Delta\, t_{kr}$.

For this relationship, the calculated value of Student's t-statistics is:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} = \frac{0{,}9993\sqrt{9-2}}{\sqrt{1-0{,}9993^2}} = 70{,}67 \quad (3)$$

With seven degrees of freedom and for the level of significance $\alpha = 0.05$, the critical table value of the statistics $t_{0.05}$ is 2.365, which confirms that there is no reason to reject the hypothesis of the existence of a linear relationship between the thermal effect of solidification Q and the solidification time $\Delta\, t_{kr}$.

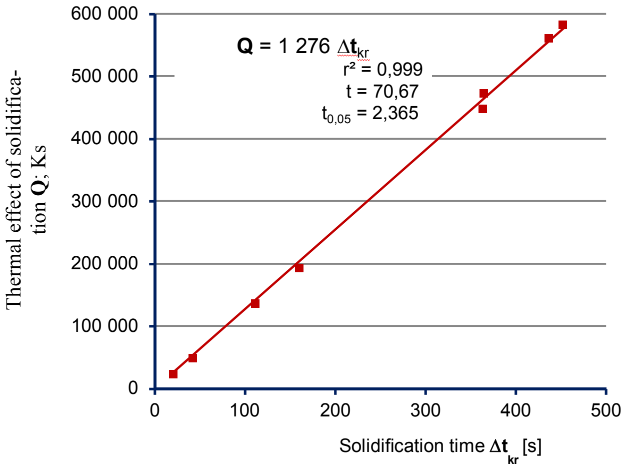

Fig. 11. Empirically determined relationship between the thermal effect of solidification **Q** and the solidification time $\Delta \mathbf{t_{kr}}$ for H282 alloy (data from melts H1 and H3 were used)

The cooling rate of H282 has a very important effect on the dendrite growth during solidification. The effect of wall thickness on the solidification process of the metallic matrix of this alloy was analyzed by measuring in a step test block the value of DAS in the center of individual steps. The results showed that the increase in solidification time from less than one minute at a wall thickness of 10 mm to over seven minutes at a wall thickness of 44 mm gave a twofold increase in the DAS parameter (Figure 12).

H282 is an alloy of the latest generation and is considered a strategic material. For this reason, data in the available sources are scarce and unreliable, this including the data on thermo-physical and technological properties in a high range of the melting and solidification temperatures, necessary for proper development of the alloy casting technology. Therefore it is expected that the results obtained in this study will be helpful in design and computer simulation of the mold filling process and solidification of castings made from this alloy.

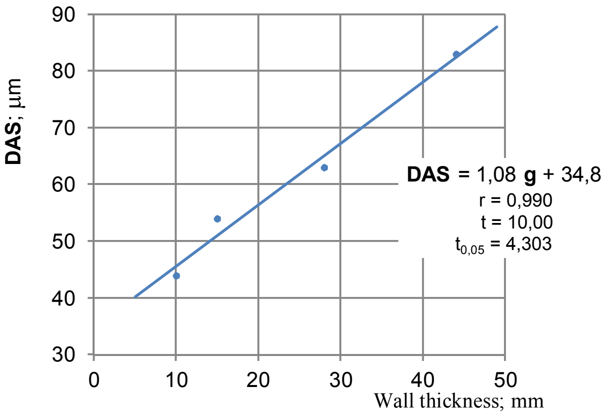

Fig. 12. Wall thickness effect on DAS in a casting made from the H282 alloy

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