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THERMAL ANALYSIS OF LOW ALLOYED STEEL FOR HEAVILY-LOADED AIRCRAFT ENIGINE TRANSMISSION GEARS

Paweł Rokicki, Kamil Dychtoń, Marcin Drajewicz, Krzysztof Raga, Andrzej Nowotnik, Krzysztof Kubiak

S u m m a r y

Heat treatment of elements with large and complex geometries generate distortions and strains inhomogeneity. Current paper focuses on material basic thermo-chemical parameters analysis in aim for prediction of AISI 9310 steel behaviour if it is about treatment of ring gears used conventionally for aircraft engine gear transmission system. Heat treatment process of heavily loaded aircraft engine transmission gears is a complicated process due to shape and size of the elements. Concerning above, current paper presents thermal analysis of AISI 9310 low alloy steel. Results of conducted research will be used as a input data for numerical simulation of cooling process. Optimal process modelling will allow eliminating of defects caused by the heat treatment process.

Keywords: heat treatment, AISI 9310, low-alloy steel, thermal analysis

Analiza cieplna stali niskostopowej stosowanej na silnie obciążone elementy przekładni napędów lotniczych

S t r e s z c z e n i e

Obróbka cieplna elementów o złożonym kształcie wprowadza duże zmiany w ich stanie naprężeń wewnętrznych. Mają wpływ na odkształcanie się obrabianych elementów uniemożliwiające często ich zastosowanie. W pracy prowadzono badania właściwości cieplnych stali AISI 9310 niezbędnych do prawidłowego opracowywania warunków obróbki cieplno-chemicznej elementów pierścieniowych kół zębatych stosowanych w przekładniach silników lotniczych. Obróbka tych elementów, z użyciem złożonego oprzyrządowania niezbędnego do prawidłowego ich zamocowania w komorze pieca próżniowego, jest procesem trudnym do realizacji. Opracowane warunki procesu obróbki cieplno-chemicznej powinny uwzględniać duże rozmiary kół zębatych przekładni oraz wymaganą powtarzalność uzyskanych profili twardości warstwy nawęglanej i hartowanej. Analiza wyników prowadzonych badań właściwości fizycznych i cieplnych stali AISI 9310, m.in. współczynnika cieplnej rozszerzalności liniowej i przewodnictwa cieplnego, a także dyfuzyjności była podstawą do opracowania modelu fizycznego umożliwiającego symulację numeryczną tego procesu. Badania doświadczalne uwzględniające wyniki symulacji numerycznej i opracowane warunki obróbki cieplno-chemicznej prowadzą do uzyskania wymaganych właściwości użytkowych warstwy nawęglonej i hartowanej próżniowo.

Słowa kluczowe: obróbka cieplna, AISI 9310, stal niskostopowa, analiza cieplna

Address: Paweł ROKICKI, PhD Eng., Kamil DYCHTOŃ, MSc Eng., Marcin DRAJEWICZ, PhD Eng., Andrzej NOWOTNIK, PhD Eng., Krzysztof KUBIAK, DSc Eng., Rzeszow University of Technology, Department of Materials Science, 2 Wincentego Pola St., 35-959 Rzeszow, e-mail: prokicki@prz.edu.pl, Krzysztof RAGA, PhD Eng., Pratt&Whitney Rzeszow, 120 Hetmanska St., 35-078 Rzeszow

1. Introduction

Every day, all over the world, jet engine producers work on turbofan concepts that are more and more efficient, lighter, lower in cost, quieter and more environmental friendly. One of the promising ideas is to modify two-shaft engine by reducing speed between the fan and LPC and LPT elements which are spinning with much higher speed [1]. Such a design assumes a use of gears that allow fan to rotate at different speed than low spool machinery. Basically fan speed goes down and bypass ratio increases and the pressure ratio is reduced what finally results in LPC and LPT speed optimization to improve performance of whole engine. The main goal of worldwide research is then to improve propulsion efficiency and therefore thrust and specific fuel consumption. Such an approach requires finding design methods and technologies on component level. One of them concerns heat treatment and thermo-chemical treatment of heavily loaded elements of transmission gear system. These operations sequentially proceed after each other from carburizing through quenching in oil to sub quenching and tempering [2, 3]. They are categorized as key operations that are forming stresses and strains distribution and gear properties. In these operations surface layer and core obtain final properties, which describe end product. Moreover it is possible to control dimensional changes through ring quenching in quenching device or press [4, 5]. Due to thin-walled gear selection and its large internal diameter the only possible and effective solution is quenching in special device on quench press to ensure good control of dimensions and mechanical properties of quenched ring. Significant question for dimensional stability at optimum stresses state is connected with besides others quench device design, respective components of pressure force acting on the hardening tool, selection of optimum press pressure and forces distribution and most important in the material meaning thermal basic parameters and behaviour of the steel itself [6]. Heat treatment and thermo-chemical treatment of large elements generate problems due to product strains and distortion of thermal and structural origin. Particular case are rings or ring gears with large diameter, with complex cross-section and carburized layer in the teeth area. Achieving suitable properties of the elements core, dimensional repeatability within required tolerances and appropriate and homogeneous thickness of carburized layer on finish product are main criteria during the manufacturing process. It appears that complex state of strains in forging with large diameters and small cross-section dimensions are the main problem in the way to achieving products of heightened sensitivity criteria. Due to above mentioned factors it is important to investigate and get to know the material to be used for so complex, in meaning of geometry and final properties, elements. Thermal analysis of some of the basic factors of the steel allow to predict structural behaviour of the material through complex technological processes introducing structural and behavioural distortions. Presented study focuses on AISI 9310 steel which is conventionally used for mentioned group of complex elements as rings and ring gears. Research methodology covers thermal analysis of presented material in meaning of heat and thermo-chemical treatment technology development.

2. Methodology

In this study, thermal properties of AISI 9310 low-alloyed steel were analysed. The ring gearbox made of AISI 9310 was divided into eight sections. Two diametrically opposing sections were selected and marked as C1 and C2, to compare the ring thermal properties in various spaces. Fig. 1 presents schematic description of the above process.

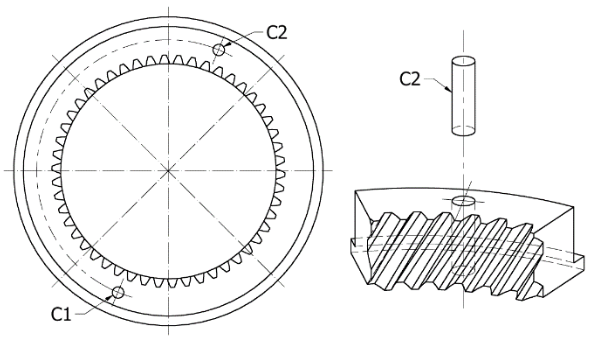

Fig. 1. Ring gear made of AISI 9310 low alloy steel – used for preparation of specimens for thermal properties investigation

The samples in the shape of cylinder were prepared to thermal diffusivity, thermal expansion and specific heat measurements from the C1 and C2 rods. The most important thermal property of steel, used for predictions of temperature gradient and residual stress distribution in the numerical simulations, is thermal conductivity [7]. This feature can be measured from the equation:

$$\lambda(T) = a(T)\cdot c_p\,(T)\cdot\rho(T) \tag{1}$$

where $a(T)$ is the thermal diffusivity, $c_p(T)$ is the specific heat and $\rho(T)$ is the density The laser flash analysis (LFA) technique was used to measure the thermal diffusivity. High precision and reproducibility, short measurement times, variable sample holders and mathematics models are outstanding features of LFA measurements over the entire application range from 20 to 2000°C. The measurement of thermal diffusivity was made in the temperature range from 20 to 1000°C with intervals of 100 degrees. As a mathematical model serving to the studies of measuring signals improved Cape – Lehman's model was used [8-10]. Three shots were done for each temperature.

To measure the specific heat the thermal analyser STA 449 Jupiter F3 (Netzsch Company) was used. The mass of sample was equal to the mass of sapphire (42 mg) and the measurement was performed in Pt-Rh crucible with Al_2O_3 liners inside the pan. The dilatometric measurements were performed in the dilatometer DIL 402C (Netzsch Company) with the calibration function. The lengths of the standard and steel samples were equal 25 mm +/- 1%. Dilatometric analysis was performed with a temperature rate of 10K/min during heating.The density was measured by the equation:

$$\rho(T) = \rho_0/(1 + \Delta L/L_0\,(T))^3 \tag{2}$$

where: ρ_0 – is density in room temperature, L_0 – length of sample, $\Delta L(T)$ – length changes with temperature and time.

In both studies (specific heat and thermal expansion analyses) the helium was used as the inert gas and the temperature range was 20-1000°C.

3. Results and discussion

Dilatometric analysis results were presented in Fig. 2 and 3. During the heating step it can be noticed that there are almost no differences in the values of thermal expansion coefficient of specimens C1 and C2.

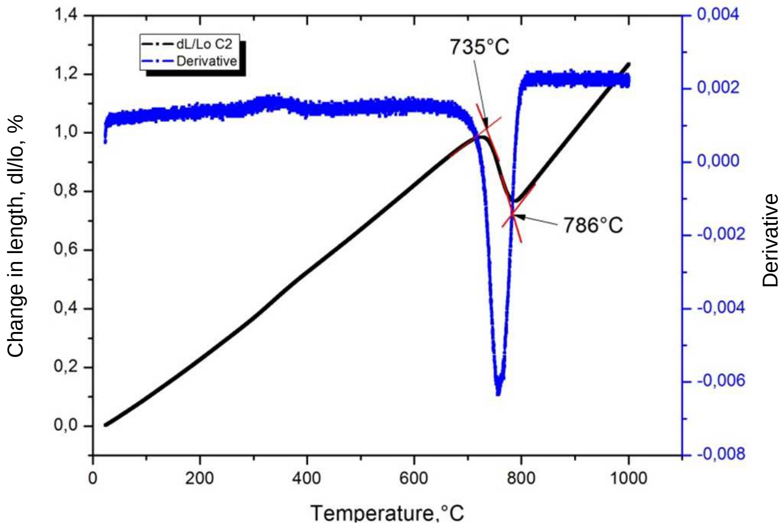

Fig. 2. Dilatometric analysis of AISI 9310 steel (specimen C1) with marked characteristic temperature values for onset and end of phase transformation in the heating process

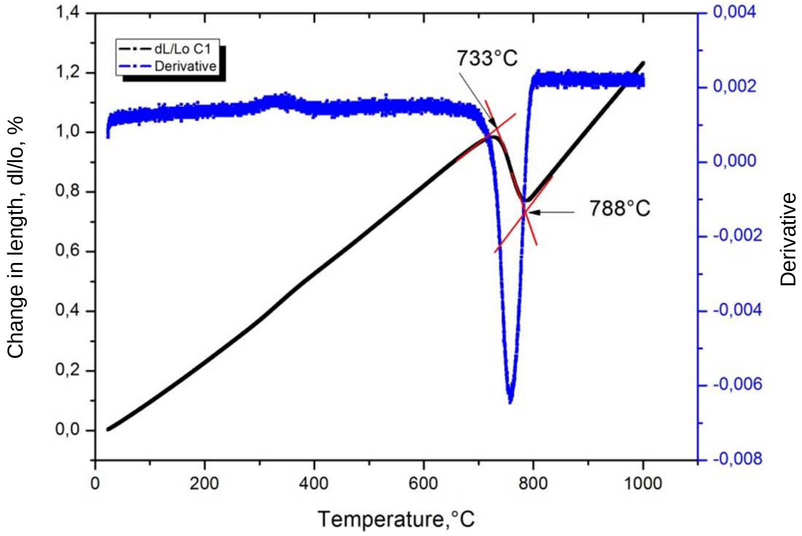

Fig. 3. Dilatometric analysis of AISI 9310 steel (specimen C2) with marked characteristic temperature values for onset and end of phase transformation in the heating process

But the onset and end of the eutectoid reaction appointed from the dilatometry curve shows small departures. This mean that local differences in phase can appear between sample C1 and C2. It can affect locally the temperature gradient during the quenching and then cause distortions. Nevertheless designated points of phase transformation for AISI 9310 coincide with the values presented in the literature. Thermal diffusivity measurements for specimens C1 and C2 are presented in Fig. 4. The average values were used to fit the curve and the standard deviation was made for three shots in each temperature from range 20 to 1000°C with intervals of 100 degrees. Additional measurement shots have been performed for room temperature. It can be noticed that the values of thermal diffusivity for each temperature are different for both C1 and C2 samples. Even if the standard deviation will be taken into account, the thermal diffusivity values still are not the same. This relation can be observed also for specific heat curves with little change. The values of specific heat for sample C1 are higher than for sample C2. For thermal diffusivity values the relation is opposite. This means that the C1 sample needs more time to heat up than the C2 sample. This finding confirms the earlier assumption about local differences in the microstructure of the samples. As presented in Fig. 5 thermal conductivity differ strongly for each sample. That cause the differences in temperature gradient during heating and quenching and may contribute to the emergence of minor changes to the dimensions of the elements, which may result in rejection of the final part. Moreover, this affects the values of residual stresses and can impact strongly on decrease of the hardness.

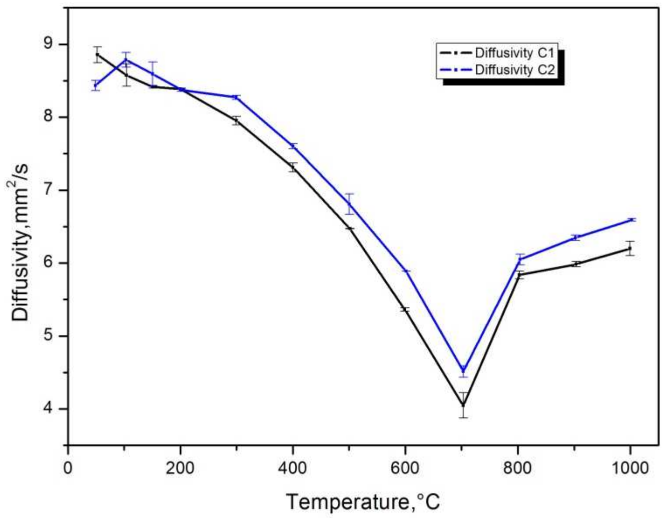

Fig. 4. Thermal diffusivity analysis of AISI 9310 steel
(specimens C1 and C2)

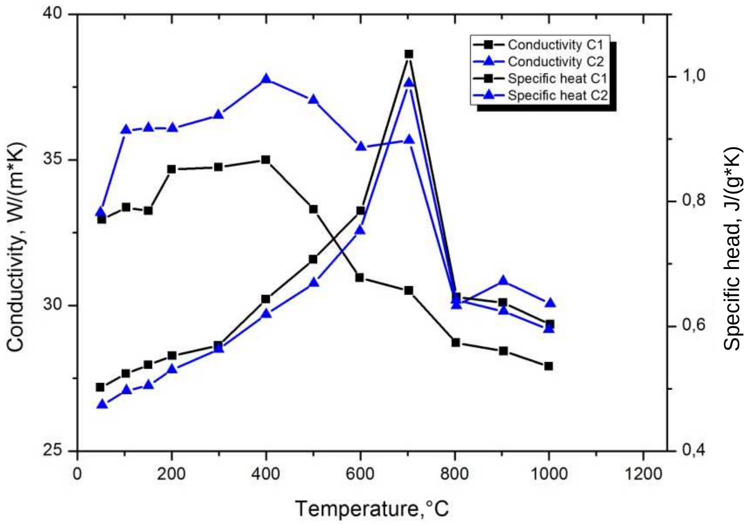

Fig. 5. Specific heat and thermal conductivity analyses of AISI 9310 steel
(specimens C1 and C2)

Analysis of the curves proves phase transformation at a temperature presented by phase diagram of AISI 9310 steel. To determine the nature of phase transformation more accurate measurements would be desired, fortunately for confirmation of basic thermal characteristic of the alloy, performed test gives enough data

4. Conclusions

The research presented in the paper fits the need of evaluation of characteristic of the material used for further thermo-chemical treatment. The issue is of a great need if it is about the distortions and strains analysis in heavily loaded elements of alloy steels. Based on performed experiments one can conclude that phase transformation in AISI 9310 steel occurs in a temperature range compatible with the phase diagram provided by literature analysis for specific steel elements. Differences in thermal diffusivity measured in the study, even after taking into account standard deviation, confirm local differences in the microstructure of the samples. This can strongly impact structural distortion factor that will be problematic in meaning of geometrical accuracy and basic mechanical properties of final part after heat treatment process.

Thermal analysis of low alloy AISI 9310 steel used for manufacturing of heavily loaded aircraft engine transmission system showed small deviations in eutectoid phase transformation temperature value. These deviations may cause changes in the microstructure and local stresses, which will cause gears geometry changes in the heat treatment process. Presented analysis of thermal properties can be used for proper technological process preparation which will lead to decrease internal stresses inhomogeneity and finally lower geometrical distortions.

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