Investigation of thermal conductivity of metal materials on view of influence of ultrasonic waves

A R Lepeshkin¹, P P Shcherbakov²

¹Central Institute of Aviation Motors, Russia, 111116 Moscow, Aviamotornaya 2
²National Research University "Moscow Power Engineering Institute" Russia, 111250 Moscow, Krasnokazarmennaya, 14

E-mail: lepeshkin.ar@gmail.com

Abstract. A devices and methods were developed to determine characteristics of thermal conductivity in metals materials on view of influence of ultrasonic waves at frequencies of 20 kHz and 2.6 MHz. A thermograph was used for investigation of the non-stationary thermal state of a conical rod and contactless measurements of its surface temperatures. The curves of heating of the tip of the conical rod and the time of heat transfer from the electric heater to the tip of the rod in experiments with an ultrasonic radiator and without it were carried out. According to the results of the research it was obtained that the thermal conductivity of a metal rod is increased by 2 times at a frequency of 20 kHz with an intensity of 50 W. The measure technique and the experimental data on the thermal conductivity of AISI-304 stainless steel in the ultrasonic wave field 2.6 MHz are given. A stationary comparative method for determining the thermal conductivity is used. As a result of the experiments it was established that the thermal conductivity of the rod increases by 2 times in the temperature range 20-100 °C in the field of ultrasonic wave. The obtained results confirm that in the alloys under the influence of ultrasonic waves on electrons and nodes of the crystal structure the contribution of the electron and lattice components of the thermal conductivity increases.

1. Introduction

The investigation of the thermal conductivity [1] in the field of action of ultrasonic (US) waves is a new and complex problem and the solution of this problem is of current importance for ultrasonic equipment operating at elevated temperatures in various technological processes used in power engineering and industry. The technological processes intensified by US waves in the gaseous medium are included combustion processes, gasification of solid fuels, processes of mass exchange and coagulation of aerosols, cleaning of flue gases and others.

The transfer of heat in metals and other solid substances has specific features. The physics of the action of ultrasound on a solid body in a simplified form is perceived as excitation of an ultrasonic wave in it with amplitude and frequency corresponding to the intensity and frequency of oscillations of the ultrasonic radiator. Usually the boundary of the beginning of the ultrasonic frequency range is assumed to be 15-20 kHz. The real ultrasonic field in a solid body is of a complex nature. An increase in the temperature and intensity of ultrasound leads to an increase in the degree of excitation of the oscillations, to an increase in their average energy, which determines the internal energy of the solid. With an increase in the internal energy of a solid body (metal) in an ultrasonic field the free electrons receive a velocity increment in the direction of propagation of the ultrasonic waves. Thus, the elastic
waves of the crystal lattice push free electrons. When interacting with an electron the phonon exchanges momentum and energy with it. Consequently, the electron receives an increase in speed in the direction of propagation of the ultrasonic wave. The motion of the free electrons in the direction of the ultrasonic wave creates an electric current. Due to the motion of electrons with the drift velocity the transfer of heat is carried out also. In this case the electrons interact with the atoms of the crystal lattice of metals and transfer heat to it.

2. The non-stationary investigation of the thermal conductivity of metal materials on view of influence of ultrasonic waves

In this paper a method for the non-stationary study of the thermal conductivity of materials in the field of action of ultrasonic waves is proposed. A device with use nonstationary method was developed to determine these characteristics which is a design with an piezoceramic radiator and a rod (waveguide) with an electric heater (figure 1). The ultrasonic piezoceramic radiator is located inside the middle part of the construction 1 and operates at a frequency of 20 kHz with an intensity of 50 W and a rod is located at the end of the construction. The research method provided for securing on the middle of the rod 2 of a variable cross section (in the form of a cone) of an electric heater 3 (with thermal insulation) consisting of several turns of a chromel wire (figure 1). The tip of the rod 2 is made in the form of a flat expanding part. The temperature and the heat transfer from the electric heater were investigated at point 4 of the tip of the rod.

![Figure 1](image.png)

**Figure. 1.** Device for non-stationary determination of the thermal conductivity of metallic materials:
1- construction, 2-rod, 3- electric heater with thermal insulation, 4-point at the tip of the rod

A thermograph was used to study the thermal state of the conical rod and contactless measurements of its surface temperatures. The temperature control of the rod with the electric heater was monitored by a computer system connected with the IRTIS-2000 thermograph. The basic model of the thermograph camera is equipped with an IR receiver cooled with liquid nitrogen. This determines its high sensitivity (not worse than 0.05 °C) in a wide range of temperatures and allows stabilizing IR receiver parameters irrespective of the ambient temperature, providing high accuracy of absolute temperature measurements. The spectral range of the chamber is 3-5 μm. The results were processed according to the developed program. A stabilized power supply was used to supply the electric heater.

The investigations of the temperature curves of the tip of the conical rod as a function of time during the transfer of heat from the electric heater in experiments with the turned on ultrasonic radiator and without it have been carried out. The curves are presented in figure 1 (to 40 s) and in figure 2 (to 250 s).
The analysis of the heating rates and the time of heat transfer was carried out from the temperature curves of the tip of the conical rod (Figure 2) at the beginning of the heating. According to the results of these studies, it was found that the thermal conductivity of a metal rod made of carbon steel, taking into account the influence of ultrasonic waves, increases by 2 times.

3. The method of stationary investigation of the thermal conductivity of metallic materials taking into account the influence of ultrasonic waves

In metals the heat is transferred by oscillations of atoms of the crystal lattice (phonons) and electrons. Therefore, the coefficient of thermal conductivity is \( \lambda = \lambda_l + \lambda_e \) consists of the lattice thermal conductivity \( \lambda_l \) and the thermal conductivity \( \lambda_e \) due to the electrons. The estimates show that in pure metals the main contribution to the thermal conductivity in the room temperature range is made by the thermal conductivity of the electron gas which exceeds the lattice thermal conductivity by almost 100 times. Transmission of energy to electrons and structural formations is carried out under the influence of US waves on a metallic material (alloy). This creates a temperature gradient along the length of the rod as a result of attenuation of the ultrasonic wave. A different degree of influence of US waves leads to the appearance of a temperature distribution in the medium. The resulting thermal conductivity also leads to a decrease in the energy of the US wave. In this paper we also used the method of stationary determination of thermal conductivity. To study the effect of ultrasonic waves with a frequency 2.6 MHz on the thermal conductivity of the AISI-304 alloy the developed experimental device was used (Fig. 4). The cylindrical rod 7 of AISI-304 stainless steel with a length \( L = 95 \text{ mm} \) and diameter \( d = 6 \text{ mm} \) is located in a tightly adherent foam cover 6 to prevent heat loss from the side surface. One end of the rod is heated by a nichrome coil 5 connected to a DC power source. The other end of the rod is in tight contact with the cold thermostat 9 in which cooling water circulates. Thermocouples 8 are...
located along the length of the. The distance between the upper and lower thermocouples is \( l = 70 \) mm. The lower end of the rod has a contact area with a diameter \( D = 20 \) mm which is mounted on a piezoceramic ultrasonic radiator 3. The piezoceramic radiator 3 is located in the oil bath 2 of the casing (heat-insulating shell) 1 for efficient transmission of the US wave to the base of the rod 7. The radiator is connected to an US generator 2.6 MHz. The temperature of the rod is measured at three points by chromel-copel thermocouples 8 connected to temperature meters 11 (TRM-200) with a measurement error of 0.1 °C. The entire construction is placed in the thermal insulation casings 1 and 6. To determine the power supplied to the heater 5 the current 12 and the voltage 13 of the source of power 14 are measured.

![Figure 4](image)

**Figure 4.** Device for stationary determination of the thermal conductivity of metallic materials: 1 - heat-insulating shell, 2 - oil bath, 3 - piezoceramic radiator, 4 - oil, 5 - electric heater, 6 - heat-insulating shell, 7 - cylindrical rod, 8 - thermocouples, 9 - thermostat, 10 - thermocouple switch, 11 - temperature meters, 12 - ammeter, 13 - voltmeter, 14 - source of power, 15 - US generator

On the basis of the Fourier law the heat flux \( Q \) through a surface area \( S \) located perpendicular to the \( x \) axis is directly proportional to the area and the temperature gradient (temperature change per unit length in the direction of the normal to this surface) and is determined by the formula:

\[
Q = \lambda \frac{\Delta t}{\ell} S
\]

To compare the obtained results the reference data on the thermal conductivity \( \lambda = 16.2 \) W/m·K for AISI 304 stainless steel in the range 20-100 °C are used.

### 3.1. The first experiment

The first experiment was conducted with the turned on US generator 15. At the same time the heater 5 was switched off. The US generator was switched on. When the stationary mode is reached the indication of the lower (hot) thermocouple is \( t_1 = 35.7 \) °C, the upper (cold) is \( t_2 = 19.7 \) °C. The temperature difference was \( \Delta t = 16 \) °C taking into account the average thermocouple indication and it can be assumed that the temperature gradient along the rod length is constant. The calculations showed that the transmitted power per sample taking into account the thermal losses to the environment was 0.2 W. In this case the value of the thermal conductivity calculated by formula (1) is equal to \( \lambda = 30.9 \) W/m·K.
The temperature difference was created by obtaining of the heat from the heated piezo-radiator \( \Delta t_1 \) and due to the transmitted energy of US waves to the conduction electrons and structural formations (\( \Delta t_2 \)) in the sample \( \Delta t = \Delta t_1 + \Delta t_2 \). To take into account the influence of US waves on the sample it is necessary to exclude the transmitted thermal power 0.105 W from the heated piezo-radiator to the sample. For this the reference data on the thermal conductivity of the sample and formula (1) are used. Thus, the transmitted energy of ultrasonic waves to the conduction electrons and structural formations in the sample was \( 0.200 - 0.105 = 0.095 \) W. This leads to the appearance of an additional temperature gradient in the sample which increases the thermal conductivity.

3.2. The second experiment
The second experiment was carried out with the turned on US generator 15 and the switched on electric heater 5. To check the results of the first experiment an another different technique was used. At the first stage of the experiment the source of power 14 was switched on for the supply of the heater 5. US generator was switched off. After entering the stationary mode the voltage at the heater \( U \), the current in the heater 1, the indication of the lower (hot) thermocouple \( t_1 \) and the indication of the upper (cold) thermocouple \( t_2 \) were measured. The average measured values are given in Table 1.

| I  | U   | P   | \( t_1 \) | \( t_2 \) | \( \Delta t \) |
|----|-----|-----|---------|---------|-------------|
| [A] | [V] | [W] | [°C]    | [°C]    | [°C]        |
| 0.77 | 4.17 | 3.21 | 113.8   | 19.43   | 94.37       |

The source of ultrasonic waves 15 was switched on in the second stage of the experiment at the same power of the heater 5. After reaching the stationary mode the previously indicated values were measured. The average values of the measured values are given in Table 2.

| I  | U   | P   | \( t_1 \) | \( t_2 \) | \( \Delta t \) |
|----|-----|-----|---------|---------|-------------|
| [A] | [V] | [W] | [°C]    | [°C]    | [°C]        |
| 0.77 | 4.17 | 3.21 | 123.3   | 19.50   | 103.80      |

In the third stage of the experiment the power of the heater 5 decreases to temperatures \( t_1 \) and \( t_2 \) shown in Table 1. The average measured values are given in Table 3.

| I  | U   | P   | \( t_1 \) | \( t_2 \) | \( \Delta t \) |
|----|-----|-----|---------|---------|-------------|
| [A] | [V] | [W] | [°C]    | [°C]    | [°C]        |
| 0.68 | 3.80 | 2.58 | 113.8   | 19.50   | 94.30       |

The difference of the electric powers supplied to the heater 5 in the second and third stages of the experiment determines the energy supplied to the sample from the US generator in the second experiment

\[
\Delta P_{\text{US}} = P_2 - P_3 = 0.63 \text{ W}
\]  

This leads to the appearance of an additional temperature gradient \( \Delta t/l \) in the sample which increases the thermal conductivity. To determine the thermal losses to the environment the data in Table 1 and reference data on the thermal conductivity of AISI-304 stainless steel were used. In an "ideal"
experiment without thermal losses it is necessary to bring the thermal power  \( P_0 = 0.620 \) W. Consequently the heat losses \( \Delta Q_{IS} \) in the first stage of the second experiment are equal

\[
\Delta Q_{IS} = 3.21 - 0.62 = 2.59 \text{ W} \quad (3)
\]

Taking into account (2) and (3) in the second stage of the second experiment the flow of thermal power from the heater 5 and US generator 15 through the cross section of the sample at a given temperature gradient is

\[
\Delta Q = \Delta P = P_2 + \Delta P_{uz} - \Delta Q_{IS} = 3.21 + 0.63 - 2.59 = 1.25 \text{ W} \quad (4)
\]

Taking into account the transferred thermal power from the heated piezo-radiator to the sample the thermal conductivity is \( \lambda = 28.3 \) W/m K.

The results of the experiments confirmed a significant increase of the thermal conductivity of the AISI-304 alloy due to the influence of ultrasonic waves on conduction electrons and structural formations. The values of the thermal conductivity of the alloy in the field of ultrasonic waves obtained in two experiments with different techniques are similar. In the first and second experiments the thermal conductivity was \( \lambda = 30.9 \) W/m K and \( \lambda = 28.3 \) W/m K. The absolute error in determining the thermal conductivity is estimated by \( \Delta \lambda = \pm 7\% \).

4. Conclusion

The methods and devices for non-stationary and stationary investigation of the thermal conductivity and thermal conductivity of materials in the field of ultrasonic waves have been developed. The devices are different designs with ultrasonic radiators and waveguides in the form of rods. In the device of the non-stationary method, a transducer operating at a frequency of 20 kHz with a power of 50 W is located inside the structure and a waveguide in the form of a conical rod is located at the end of the structure. A thermograph was used for investigation of the nonstationary thermal state of a conical rod and contactless measurements of its surface temperatures. The curves of heating of the tip of the conical rod and the time of heat transfer from the electric heater to the tip of the rod in experiments with an ultrasonic transducer and without it were carried out. According to the results of the research it was obtained that the thermal conductivity of a metal rod is increased by 2 times. The developed device at a frequency of 2.6 MHz was used for the stationary determination of the thermal conductivity of a cylindrical rod made of stainless steel AISI-304 in the field of an ultrasonic wave. As a result of the experiments it was established that the thermal conductivity of the rod increases on average by 2 times in the temperature range 20-100 °C in the field of ultrasonic waves. The obtained results confirm that the thermal conductivity of metallic materials increases with allowance for the effect of ultrasonic waves.

References
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