

# The Effect of Thermal Conductivity on The Depth of Laser Transformation Hardened Zones

L.J. Yang

School of Mechanical and Production Engineering, Nanyang Technological University,  
Nanyang Avenue, Singapore 639798, Republic of Singapore.

## Abstract

*An experimental study was carried out to determine the thermal conductivity of Assab-DF2 cold work tool steel in its "as-received" soft annealed condition, as well as in the hardened and tempered to 40, 50 and 60 HRC conditions, with test temperature ranged from 100 to 700 °C. It was found that the thermal conductivity of the steel increased initially with increasing temperature until at about 300 °C. It then decreased gradually with further increase in temperature, up to 700 °C. It also decreased with increasing hardness. The average thermal conductivity values observed are 34.6, 34.1, 33.7 and 32.7 W/mK for the specimens at the "as-received", 40, 50 and 60 HRC conditions respectively. The present work therefore explains, at least partially, why the "pre-hardened" specimens exhibited a greater depth and width of the hardened zones after laser transformation-hardening in a previous study.*

**Keywords:** Laser-transformation-hardening; Thermal-conductivity; Tool-steel; Depth of hardened-zone; Heat-treatment.

## 1 Introduction

In laser transformation hardening, a thin layer of the substrate is rapidly heated well into the austenitizing temperature range by laser heating and is cooled subsequently at a very fast rate, due to self-quenching by conduction into the bulk body, to produce a martensitic structure. The three most important criteria for laser heat-treating are [1]: (i) the temperature for the zone being hardened must reach well into the austenitizing range; (ii) between the heating and cooling cycles, the substrate should be maintained at the austenitizing temperature long enough for carbon diffusion to take place; and (iii) there should be sufficient mass for the cooling rate by self-quenching to be such as to satisfy the critical quenching-rate requirement.

The major independent process variables for laser transformation heat-treatment include: (i) the

absorptivity of the coating and the substrate; (ii) the power of the incident laser beam; (iii) the diameter or size of the incident laser beam; and (iv) the speed of traverse across the surface of the substrate. The dependent variables are considered to be: (i) the depth and gradient of the hardness; (ii) the geometry and microstructure of the heat-affected zone; and (iii) the metallurgical properties of the laser heat-treated material.

In the previous study of the laser transformation - hardening of specimens made of Assab DF-2 materials (equipment to AISI 01), in both the "as-received soft-annealed" condition and in the "pre-hardened to 40 HRC" [2], it was found that the "pre-hardened" specimens exhibited a greater depth and width of the hardened zones and a higher surface-hardness after laser transformation-hardening, compared with the "as-received" specimens. The "pre-hardened" specimens were found also to be less sensitive to the effects of beam intensity.

In order to provide a satisfactory explanation to the above-mentioned experimental observation, an experimental study was carried out to determine the thermal conductivity of Assab-DF2 cold work tool steel in its "as-received" soft annealed condition, as well as in the hardened and tempered to 40, 50 and 60 HRC conditions. This is because the thermal conductivity of the material is a major factor to be considered from the theory of heat transfer, as will be described in Section 2.

## 2 Heat transfer theory

The general heat conduction equation for the temperature T as a function x, y, z and t is: [3]

$$\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + q_i = \rho c \frac{\partial T}{\partial t} \dots \dots \dots (1)$$

Here, k is the thermal conductivity, ρ is the density, c is the specific heat per unit mass, and q<sub>i</sub> is the rate of internal heat generation per unit volume. If k is taken as a constant, then Eq. 1 reduces to

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q_i}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \dots\dots\dots(2)$$

If the rate of internal heat generation  $q_i$  is zero, then the equation of conduction of heat (Eq.2) is reduced to the Fourier Equation (Eq.3):

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \dots\dots\dots(3)$$

where  $\alpha = \frac{k}{\rho c} \dots\dots\dots(4)$

and  $\alpha$  is the thermal diffusivity of the workpiece.

In laser transformation hardening, the following two solutions for one-dimensional heat flow are of interest.

### 2.1 Temperature due to an instantaneous point source

The solution to Eq.3 for an instantaneous point source of strength P at (x', y' z') at t=0 in an infinite solid is [4]:

$$T = \frac{P}{8(\pi\alpha t)^{3/2}} e^{-\frac{(x-x')^2+(y-y')^2+(z-z')^2}{4\alpha t}} \dots\dots(5)$$

As  $t \rightarrow 0$ , this expression tends to zero at all points except (x',y' z'), where it becomes infinite.

The temperature distribution in the y-z plane and passing through the point source located at (0, 0, 0) is given by Eq. 6.

$$T = \frac{P}{8(\pi\alpha t)^{3/2}} e^{-\frac{(y^2+z^2)}{4\alpha t}} \dots\dots\dots(6)$$

where T is the temperature at point (0, y, z) at time t, P is the strength of the point source.

### 2.2 Temperature due to surface heating by a laser beam of diameter $D_b$ .

The temperature T at point (0, 0, z), when heat is supplied at the rate q per unit time per unit area, for  $t > 0$  over the circle  $x^2+y^2 < a^2, z = 0$  is [4]:

$$T = \frac{2q\sqrt{\alpha t}}{\rho c \alpha} \left\{ \text{ierfc}\left(\frac{z}{2\sqrt{\alpha t}}\right) - \text{ierfc}\left(\frac{\sqrt{z^2+a^2}}{2\sqrt{\alpha t}}\right) \right\} \dots\dots\dots(7)$$

where  $a = 0.5 D_b$ , z = depth of the hardened zone and ierfc (x) is an integral function of the complementary error function.

## 3 Thermal conductivity measurement

The experimental method adopted in this project for the determination of the thermal conductivity of the steel specimens is the steady state longitudinal heat flow method. In this method, the experimental arrangement is so designed that the flow of heat is only in the axial direction of a rod specimen. The radial heat loss or gain of the specimen is prevented or minimized and evaluated. Under steady state conditions and assuming no radial heat loss or gain, the thermal conductivity is determined by Eq. (8)[5]:

$$k = \frac{-qdx}{A dt} \dots\dots\dots(8)$$

where

- k = Average thermal conductivity corresponding to the temperature  $(1/2)(T_1 + T_2)$
- dt =  $T_1 - T_2$
- q = Rate of heat flow
- A = Cross-sectional area of the specimen
- dx = Distance between points of temperature measurements for  $T_1$  and  $T_2$

This method involves a source of heat at a constant temperature which is supplied at one end of the rod to the other end, where a heat sink at a lower constant temperature is located. The radial heat loss or gain of the rod should be negligible. In order to calculate the thermal conductivity from Eq.(8), it is necessary to measure the rate of heat flow into the rod, the cross-sectional area, the temperatures at least two points along the rod (temperatures at three points were measured for this study) and the distance between points of temperature measurement.

Furthermore, the measurement is made under a vacuum of 15 mbar to prevent heat loss by gas conduction and convection. The heat is supplied to one end of the specimen by a ceramic fiber radiant heater. The temperatures at the three points along the test rod are measured by means of thermocouples. To prevent radiation heat loss, a guard tube surrounding the specimen with controlled band heaters is utilized. The band heaters are maintained at the same temperature as the test specimen so as to eliminate the temperature gradient which might contribute to heat loss radially. Ceramic fiber insulation is used to fill the space between the rod specimen and the guard tube. The guard tube should have the same temperature distributed along it as does the rod specimen to prevent temperature gradient.

The rate of heat flow into the specimen is determined by measuring the power input into the ceramic fiber heater at the free end of the rod specimen [6]. Figure 1 shows a schematic drawing

for experimental measurement of thermal conductivity of DF-2 steel specimens.

#### 4 Experimental results

Rods of 1 inch (25.4 mm) diameter and length of 340 mm, made of Assab DF-2 tool steel (equivalent to AISI 01) were prepared and used as test specimens for the experiment. The Assab DF-2 tool steel specimens are in the "as-received" soft annealed condition with a hardness of 18 HRC; as well as hardened and tempered to 40, 50, and 60 HRC conditions, which were achieved with tempering temperatures of about 550°C, 400°C and 200°C respectively. Three samples were prepared for each type of material. Table 1 shows a summary of the types of test specimen used. The typical compositions of Assab DF-2 are: C 0.90, Mn 1.20, Cr 0.50, W 0.50 and V 0.10.

**Table 1.** Types of test specimen

| S/N | Specimen Types                           | Qty |
|-----|--|-----|
| 1   | Assab DF-2 (As-received, soft annealed)  | 3   |
| 2   | Assab DF-2 (40 HRC) (Tempered at 550 °C) | 3   |
| 3   | Assab DF-2 (50 HRC) (Tempered at 400 °C) | 3   |
| 4   | Assab DF-2 (60 HRC) (Tempered at 200 °C) | 3   |
| 5   | AISI 1045 (Annealed)                     | 3   |

The measured thermal conductivity values of Assab DF-2 tool steel, calibrated against the thermal conductivity values obtained with an AISI 1045 steel, at "as-received" condition and at hardness of 40, 50 and 60 HRC are tabulated in Table 2 [7].

**Table 2.** Thermal conductivity values obtained for Assab DF-2 tool steel specimens.

| Temp °C | Thermal Conductivity (W/mK) |            |            |            |
|---------|-----------------------------|------------|------------|------------|
|         | As-rec'd (a)                | 40 HRC (b) | 50 HRC (c) | 60 HRC (d) |
| 100     | 34.3                        | 33.4       | 33.0       | 31.8       |
| 200     | 36.0                        | 35.2       | 34.7       | 33.4       |
| 300     | 36.9                        | 36.7       | 36.0       | 34.5       |
| 400     | 36.5                        | 36.0       | 35.2       | 34.5       |
| 500     | 34.3                        | 33.8       | 33.7       | 33.3       |
| 600     | 32.5                        | 32.1       | 31.9       | 31.1       |
| 700     | 31.6                        | 31.2       | 31.1       | 30.2       |
| Av      | 34.6                        | 34.1       | 33.7       | 32.7       |
| % Redn* | -                           | 1.45       | 2.60       | 5.49       |

Note 1: (a) soft-annealed; (b) tempered at 550 °C; (c) tempered at 400 °C; (d) tempered at 200 °C

Note2: \* % reduction based on the average value from the "as-received", samples.

It can be seen from Table 2 that for Assab DF-2 tool steel specimens, both in the "as-received" and in the hardened and tempered conditions, the thermal conductivity values increase as the testing temperature is increased from 100 to about 300 °C; and decrease when the testing temperature is further increased, up to 700 °C. The maximum thermal conductivity values observed are 36.9, 36.7, 36.0, and 34.5 W/mK for the specimens at the "as-received", 40, 50 and 60 HRC conditions respectively, all at a temperature of 300 °C. The thermal conductivity value of 34.5 W/mK is also observed at 400 °C for the 60 HRC condition specimen. On the other hand, the minimum and average thermal conductivity values observed for the same four types of specimen are: 31.6, 31.2, 31.1 and 30.2, all measured at 700 °C; and 34.6, 34.1, 33.7 and 32.7 respectively.

It is obvious that Assab DF-2 tool steel specimens in the "as-received" condition have a higher thermal conductivity value as compared with those in the hardened and tempered conditions. For the hardened and tempered specimens, specimens which are hardened and tempered to 60 HRC have a lower thermal conductivity value as compared with those hardened and tempered to lower hardness values, i.e. 50 and 40 HRC. The percentage reduction of the thermal conductivity value is 1.45%, 2.60% and 5.49% respectively for the hardened to 40, 50 and 60 HRC specimens as compared with that in the "as-received" condition.

#### 5 Discussion

##### 5.1 Effect of microstructures

It should also be noted that Assab DF-2 tool steel is delivered in the soft annealed condition to facilitate machining. It is then hardened and tempered to various hardness values, depends on its application. To obtain a higher hardness value, a lower tempering temperature is used. The tempering temperatures which are used for obtaining hardness values of 60, 50 and 40 HRC are about 200, 400 and 550 °C respectively. The microstructures of the steel in the "as-quenched", i.e. hardened condition, is untempered martensite with a small amount of carbides and retained austenite. When it is further tempered, the micro-structures will be changed to tempered martensite with different degrees of hardness, depending on the tempering temperature [8]. Hence the different thermal conductivity values exhibited by the different specimens are due to their different micro-structures.

## 5.2 Other published work

Ref [9] has presented a set of thermal conductivity values obtained from an oil hardening non-deforming steel, with a composition of C 0.789, Cr 0.645, Mn 0.592, P 0.022, S 0.020 and Si 0.177, in the as-quenched, tempered at various temperatures and in the annealed conditions. The test temperatures range from 360 to 544 °K. The average thermal conductivity values, computed from the data listed under Curves 4 to 14 on pp. 1127 of ref [9], are shown in Table 3.

**Table 3.** Average thermal conductivity values of an oil-hardening non-deforming steel, computed from the data listed under Curves 4 to 14 on pp. 1127 of ref [9].

| S/N | Temp Range °K | Heat-treatment Conditions | Av Ther. Cond. (W/mk) | % Redn* |
|-----|---------------|---------------------------|-----------------------|---------|
| 1   | 360-389       | Oil-quenched from 790 °C  | 27.3                  | 29.3    |
| 2   | 363-391       | Tempered at 150 °C        | 28.5                  | 26.2    |
| 3   | 360-421       | Tempered at 200°C         | 30.5                  | 21.0    |
| 4   | 371-466       | Tempered at 250 °C        | 34.3                  | 11.1    |
| 5   | 367-499       | Tempered at 300°C         | 37.7                  | 2.3     |
| 6   | 370-532       | Tempered at 350 °C        | 37.5                  | 2.9     |
| 7   | 371-548       | Tempered at 400 °C        | 37.1                  | 3.9     |
| 8   | 372-510       | Tempered at 500 °C        | 38.6                  | 0       |
| 9   | 371-535       | Tempered at 600 °C        | 38.2                  | 1.0     |
| 10  | 371-538       | Tempered at 700 °C        | 38.9                  | -0.7    |
| 11  | 371-544       | Annealed at 730 °C        | 38.6                  | -       |

Note: \* % reduction of thermal conductivity value based on the annealed samples

Table 3 again shows that the thermal conductivity of the oil-hardening non-deforming steel has a higher value, i.e. 38.6 against 27.3 W/mK, when it is in the annealed condition as compared with that in the as-quenched condition. The thermal conductivity value also increases as the tempering temperature is increased. These agree with the trend obtained from the present study of Assab DF-2 tool steel. However, the percentage reduction of the thermal conductivity values for the hardened and tempered

specimens based on the annealed one can vary up to 29.3% as indicated in Table 3. The percentage reduction for those specimens in the as-quenched and tempered at 250 °C and below conditions are especially significant.

## 5.3 The effectiveness of thermal conductivity on the depth of the hardened zones

The first term of Eq.6 indicates that T is proportional to the term  $\frac{P}{8(\pi\alpha t)^{3/2}}$  or inversely

proportional to  $\alpha^{1.5}$  if other variables in the term are held constant. Similarly, the first term of Eq.7

indicates that T is proportional to the term  $\frac{2q\sqrt{\alpha t}}{\rho c \alpha}$

(i.e.  $\frac{2q\sqrt{t}}{\rho c \alpha^{0.5}}$ ) or inversely proportional to  $\alpha^{0.5}$ . As

the depth of laser hardening depends on the extent of heat penetration to reach the austenitising temperature, the depth of the hardened zones should vary inversely to the  $\alpha$  values, ranging from  $\alpha^{0.5}$  to  $\alpha^{1.5}$ . Since  $\alpha = \frac{k}{\rho c}$ , as indicated by Eq.4, the depth

of the hardened zones should also vary inversely with the thermal conductivity k, again ranging from  $k^{0.5}$  to  $k^{1.5}$ .

It should also be noted that  $\alpha$  depends also on  $\rho c$ .  $\rho$  decreases with increase in temperature. However for the same temperature with the same material but with different hardness value or micro-structures, the present experimental setup is unable to measure the changes in the  $\rho c$  values, if any.

It is noted in Table 2 that the percentage reduction of thermal conductivity value for the hardened to 60 HRc specimens, based on the average value from the "as-received" samples, is 5.49%. However, the effect of the reduction in thermal conductivity value on the depth of the hardened zone could be greater if one considers the exponential power of 1.5. Furthermore, it should also be noted that the percentage reduction of thermal conductivity value of hardened specimens could be as high as 29.3% as indicated in Table 3. The present work therefore explains, at least partially, why the "pre-hardened" specimens exhibited a greater depth and width of the hardened zones after laser transformation-hardening in the previous study [2].

## 6 Conclusions

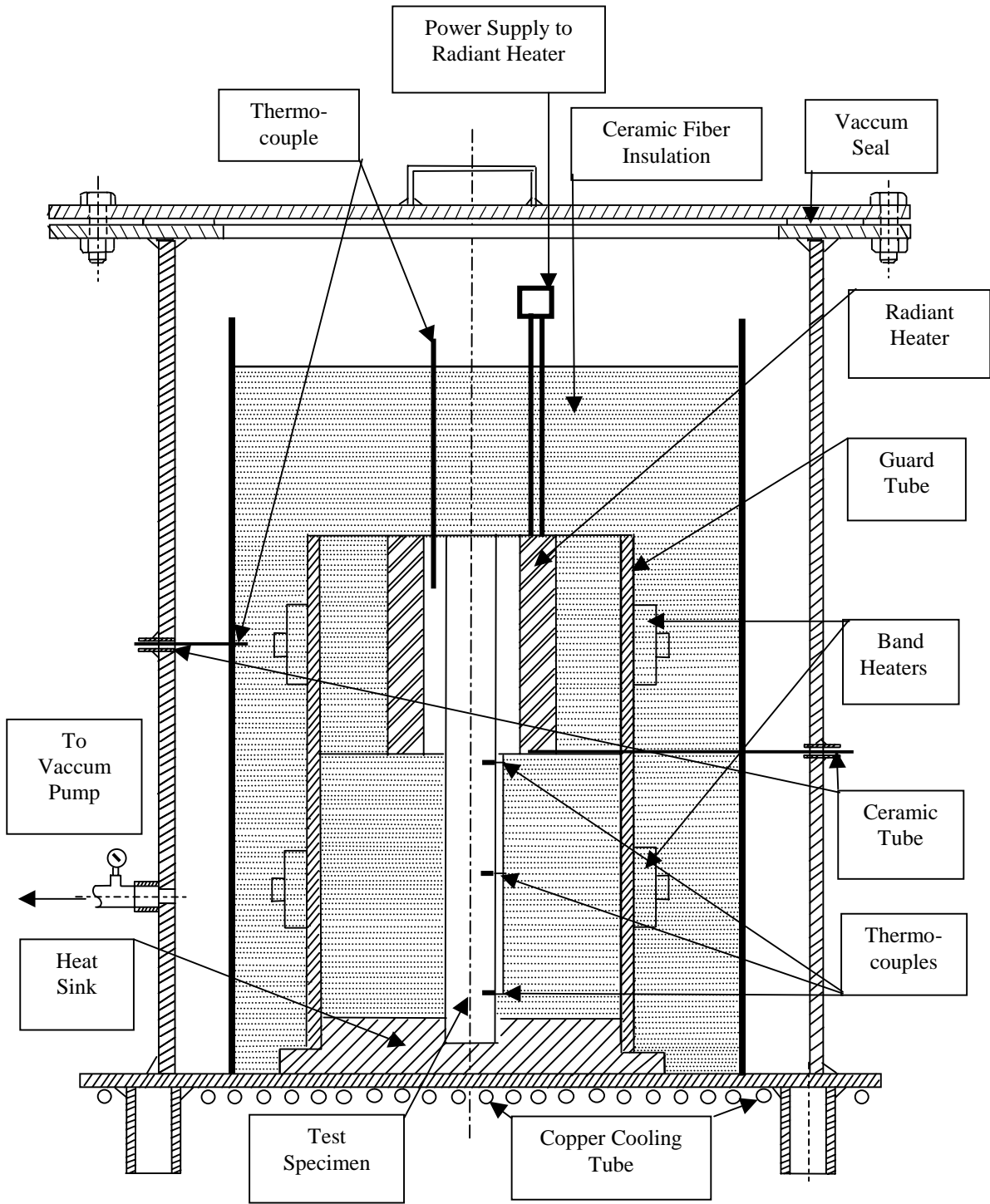
An experimental study was carried out to determine the thermal conductivity of Assab-DF2 cold work tool steel in its "as-received" soft annealed condition, as well as in the hardened and tempered to 40, 50 and 60 HRc conditions. An experimental

test rig was built and rods of 25.4 mm (1 in.) diameter and length of 340 mm were used as test specimens, with test temperature ranged from 100 to 700 °C.

It was found that the thermal conductivity of Assab DF-2 cold work tool steel increased initially with increasing temperature until at about 300 °C. It then decreased gradually with further increase in temperature, up to 700 °C. The thermal conductivity of the steel also decreased with increasing hardness. The average thermal conductivity values observed are 34.6, 34.1, 33.7 and 32.7 W/mK for the specimens at the "as-received", 40, 50 and 60 HRc conditions respectively. Since the "as-received" specimens have higher thermal conductivity values as compared with the hardened ones (i.e. 34.6 W/mK against 32.7 W/mK for the 60 HRc specimen for an example), the present work therefore explains, at least partially, why the "pre-hardened" specimens exhibited a greater depth and width of the hardened zones after laser transformation-hardening in the previous study.

## References

1. L.J. Yang, S. Jana and S.C. Tam, Laser transformation hardening of tool-steel specimens, *Jln of Materials Processing Technology*, 21 (1990) pp. 119-130.
2. L.J. Yang, S. Jana and S.C. Tam, The effects of pre-hardening on the laser transformation hardening of tool-steel specimens, *Jln of Materials Processing Technology*, 25 (1991) pp. 321-332.
3. D.R. Pitts and L.E. Sissom, *Theory and problems of heat transfer*, Mc-Graw Hill, 1983.
4. H.C. Carslaw and J.C. Jaegar, *Oxford University Press*, 2<sup>nd</sup> Ed. 1959.
5. E.C. Guyer, *Handbook of Applied Thermal Design*, McGraw-Hill, New York, 1988.
6. F.P. Incropera and D.P. DeWitt, *Fundamentals of Heat Transfer*, John Wiley & Sons, New York, 1981.
7. L.J. Yang, Thermal conductivity measurement of Assab DF-2 cold work tool steel, *Proceedings 1<sup>st</sup> International conference on thermophysical properties of materials (TPPM99)*, Editor: P. Hing, pp. 39-44, Nanyang Technological University, 1999.
8. K.E. Thelning, *Steel and its heat treatment*, Bofors Handbook, Butterworths, 1975.
9. Touloukian, Y.S. and C.Y. Ho, Eds, *Thermophysical Properties of Matter*, Plenum Press, New York, Vol. 1, *Thermal Conductivity of Metallic Solids*, 1972.



**Figure 1. Schematic drawing for the experimental measurement of thermal conductivity of DF-2 steel specimens.**