THE INFLUENCE OF HEATING RATE ON THE COEFFICIENT OF LINEAR THERMAL EXPANSION OF A 0.087% C AND 0.511% Mn STEEL

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Abstract: *This article contains the results of the dilatometric analysis carried out on a steel with 0.087% C and 0.511% Mn (Si, Cr, Ni, Mo, Al, Cu, V and W, under 0.1%) to determine the coefficient of linear thermal expansion (CTE), depending on the heating rate. For such research, the authors have used a Fe-C alloy intended for obtaining dual-phase stees with low-manganese (less than 1% Mn). The dilatometric analysis were performed with a dilatometer DIL Expedis-402 SUPREME on cylindrical specimens (5 x 25 mm), heated in a 30 ÷ 980˚ C, with heating rates of 1, 3, 5, 10 and 30˚C/min, while the coefficient of linear thermal expansion was determined for temperatures between 30 and 700˚ C.*

Keywords: *coefficient of linear thermal expansion (CTE), dilatometric analysis.*

1. Introduction

Knowing the properties and factors on which materials depend on has a particular importance for their optimal use. The use of different materials in industrial activity depends directly on their property values, as determined by laboratory tests or through technological samples. The properties of the material influence the calculation of strength, the calculation of parameters of technological process, as well as the indications on the reliability of the product which has been designed.

Physical properties determine the behavior of materials under some physical phenomena (heat, electric field, magnetic field, light field etc.) and are of particular importance in selecting and using materials in different domains such as aeronautics, oil industry, electronics, nuclear industry, automobile industry etc. Thermal properties of metals and alloys are defined as measurements which specify the behavior of materials in the presence of the thermal field. One of the most important thermal property is the materials expansion, as a consequence of the increasing the average distance between atoms with increased temperature; as the temperature increases, the average distance of separation between the atoms (r_{av}) increases and leads to the phenomenon of thermal expansion. When the temperature increases with δT, the average distance of separation between atoms increases with δr_{av} (proportional to δT). If the total length L_o consists of N atoms, $L_o = Nr_{av}$, then L_o is modifying with δL, which will be proportional to NδT, so with $L_o\delta T$. The constant of proportionality is the *coefficient of linear thermal expansion* "α", which is defined as the variation of the length on the change in temperature [1, 2]:

$$\alpha = \frac{1}{L_o} \cdot \frac{\delta L}{\delta T} \tag{1}$$

In its simplest form, the coefficient of linear thermal expansion (CTE) of any material can be defined as the fractional increase in length (linear dimension) per unit risen in temperature. The SI units of this quantity are K^{-1} and typical values for metals and alloys are in the range $10 \cdot 10^{-6}$ to $30 \cdot 10^{-6}$ K^{-1}, [3, 4, 5].

The study of the literature reveals a number of mathematical relationships to calculate the coefficient of linear thermal expansion. They can be grouped into two major categories, if the expansion occurs at variations of temperature or at a single temperature, [3, 4, 5]:

1. Definition over a temperature range. Consider a specimen of material with initial length L_o at temperature T_o which expands to L_1 at T_1, and then to L_2 at T_2, (Figure 1).

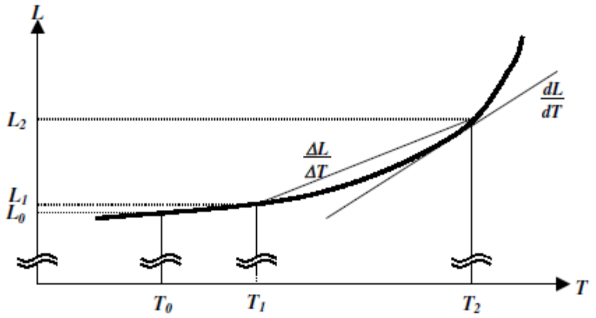

Figure 1: *Change in length (L) of a specimen of metallic material as a function of temperature (T),* [3].

The most general definition is that given by the ASTM E 473-11a, respectively "average" coefficient of linear expansion [3, 4, 5]:

$$\alpha(\Delta T) = \frac{(L_2 - L_1)/L_o}{T_2 - T_1} = \frac{1}{L_o} \cdot \frac{\Delta L}{\Delta T} \qquad (2)$$

where, $\alpha(\Delta T)$ is related to the slope of the chord between two points on the curve of length against temperature (figure 1), and so represents the expansion over the particular temperature range from T_1 to T_2. Furthermore, the fractional increase in length is calculated by dividing the increase in length by the length at T_o. It is thus necessary to specify all three temperatures when quoting the value of CTE.

2. Definition at a single temperature. In contrast to the previous definitions, the true coefficient of linear thermal expansion (also referred to as thermal expansivity) is related to the derivative dL/dT at a single temperature. This is the slope of the tangent to the curve of length against temperature (Figure 1); so, the true coefficient can thus be defined as follows [3]:

$$\alpha(T) = \frac{dL/L}{dT} = \frac{1}{L} \cdot \frac{dL}{dT} \qquad (3)$$

In order to determine the coefficient of thermal expansion there is required the measurement of two physical quantities, i.e. the expansion and the temperature for a metallic specimen subjected to a proper heat cycle, [2, 3, 4, 5].

The dilatometric analysis (mechanical dilatometry) is one of the oldest and most commonly methods used to measure the thermal expansion. The displacement of the specimen (expasion) with the temperature is transmitted mechanically to a sensor located away from heat; with the data colected by the sensor it will be generated a dilatometric curve (displacement – temperature curve), from which, then, the coefficient of linear thermal expansion could be calculated.

2. Experimental details

The coefficient of linear thermal expansion (CTE) is a basic physical quantity that can have a considerable importance in some industrial applications of a steel; in the literature are found values of this coefficient for a wide range of metals and alloys. However, for a correct use of the data, especially in the design phase of a product, it is necessary to have a correct and accurate evaluation of the thermal expansion of a specific metallic material for certain ranges of temperatures; In addition, literature is very poor in data on the influence of heating rate on this physical quantity.

The dual phase steels, introduced in industrial activities in the mid-70^s of the 20th century, are basically alloys with a low carbon content which have a structure consisting of a soft and tenacious ferrite matrix with homogeneously dispersed martensite (approx. 10 35%) and a small amount of residual austenite. Because of their properties (work hardening very fast at small stress, low yield strength, high tensile strength, very small $R_{p0,2}/R_m$ ratio, about 0.5), these steels exhibit significant practical benefits and hence are increasingly used in very different areas (shipping industry, oil industry, construction, etc.), the main beneficiary of these materials being automotive. The dual phase steels products have generally a lower percentage of carbon, less than 0.12%, between 1.0% and 3.5% manganese, and elements like V, Cr, Mo, Nb, Ti are found in the chemical composition in the proportions below 1%; in recent years there have been studies on steel with manganese content less than 1% (0.5 ÷ 1% Mn), [6, 7, 8].

Research carried out worldwide for creating and use of some dual phase steels with low content of manganese (less than 1%), have led to choose a commercial steel to fit into these features, material for which to determine the coefficient of linear thermal expansion (CTE), then to undergo intercritical quenching in order to obtain a ferrite-martensite structures characteristic to dual phase steels. This alloy has the following chemical composition (weight %): Fe, 0.087 C, 0.511 Mn, 0.091 Si, 0.0036 P, 0.0039 S, 0.029 Cr, 0.005 Mo, 0.049 Ni, 0.003 Al, 0.082 Cu, 0.003 V, 0.003 W (determined with a FOUNDRY-MASTER Xpert spectrometer produced by Oxford Instruments Analytical GmbH, Germany), the initial structure composed of 85.30% ferrite and 14.70% pearlite.

The dilatometric analysis was carried out on a Expedis DIL 402-SUPREME dilatometer, produced by the company NETZSCH Gerätebau GmbH (Germany), existing in the "Laboratory for Advanced Research Relating to Metallic and Nonmetallic Material Characterization" from Stefan cel Mare University of Suceava. The analyses were performed on cylindrical specimens (5 x 25 mm), continuously heated in the temperature range of 30 ÷ 980° C, with heating rates (v_{htg}) of 1, 3, 5, 10 and 30° C/min, in a nitrogenous atmosphere (100 ml/min N_2) and with a load at the specimen of 200 mN; for each heating rate being used six specimens.

3. Results and discussion

The data obtained with the dilatometer were processed with the NETZSCH Proteus ® Software 7.1.0., with which first the dilatometric curves were drawn and then there were determined values of the coefficient of linear thermal expansion (CTE), Figure 2. These values had been determined for temperatures ranges between 30 and 700 C, as follows: 30÷ 100 °C, 30 ÷ 200 °C, 30 ÷ 300 °C, 30 ÷ 400 °C, 30 ÷ 500 °C, 30 ÷ 600 °C și 30 ÷ 700 °C.

The values of the coefficient of linear thermal expansion (CTE), depending on the heating rate, for the above temperature ranges are shown in Table 1; analyzing these results, drawn in Figure 3, reveals the following:

- for the same heating rate, the value of the coefficient of linear thermal expansion (CTE) increases with temperature; in the case of very low heating rates (1 °C/min, 3 °C/min), the increase of the value of CTE was small, uniform and constant, but for higher heating rates (10 °C/min, 30 °C/min), CTE grew strongly for the first three intervals (30 ÷ 100 °C, 30 ÷ 200 °C and 30 ÷ 300 °C) after which the increase was receding, but constant and uniform; e.g., for v_{htg} = 1 °C/min, there was an increase by, 20.79% for CTE values determined on the 30 ÷ 100 °C heating range, compared to those established for the 30 ÷ 700 °C heating range, for v_{htg} = 5 °C/min this increase was 23.56% and for v_{htg} = 30 °C/min the increase was 81.12%;

- for the same range of temperatures, the value of the coefficient of linear thermal expansion (CTE) decreased with the increasing of the heating rate, though this has become less pronounced with increasing of temperature range; for 30 ÷ 700 °C range the values of CTE, for all five rates, were almost equalized. Between the values of CTE determined for v_{htg} = 1 ˚C/min and those established for v_{htg} = 30 ˚C/min there was a reduction of:

- 34,69% for the interval 30 ÷ 100 ˚C;
- 11,87% for the interval 30 ÷ 200 ˚C;
- 6,48% for the interval 30 ÷ 300 ˚C;
- 4,42% for the interval 30 ÷ 400 ˚C;
- 3,71% for the interval 30 ÷ 500 ˚C;
- 2,68% for the interval 30 ÷ 600 ˚C;
- 1,62% for the interval 30 ÷ 700 ˚C.

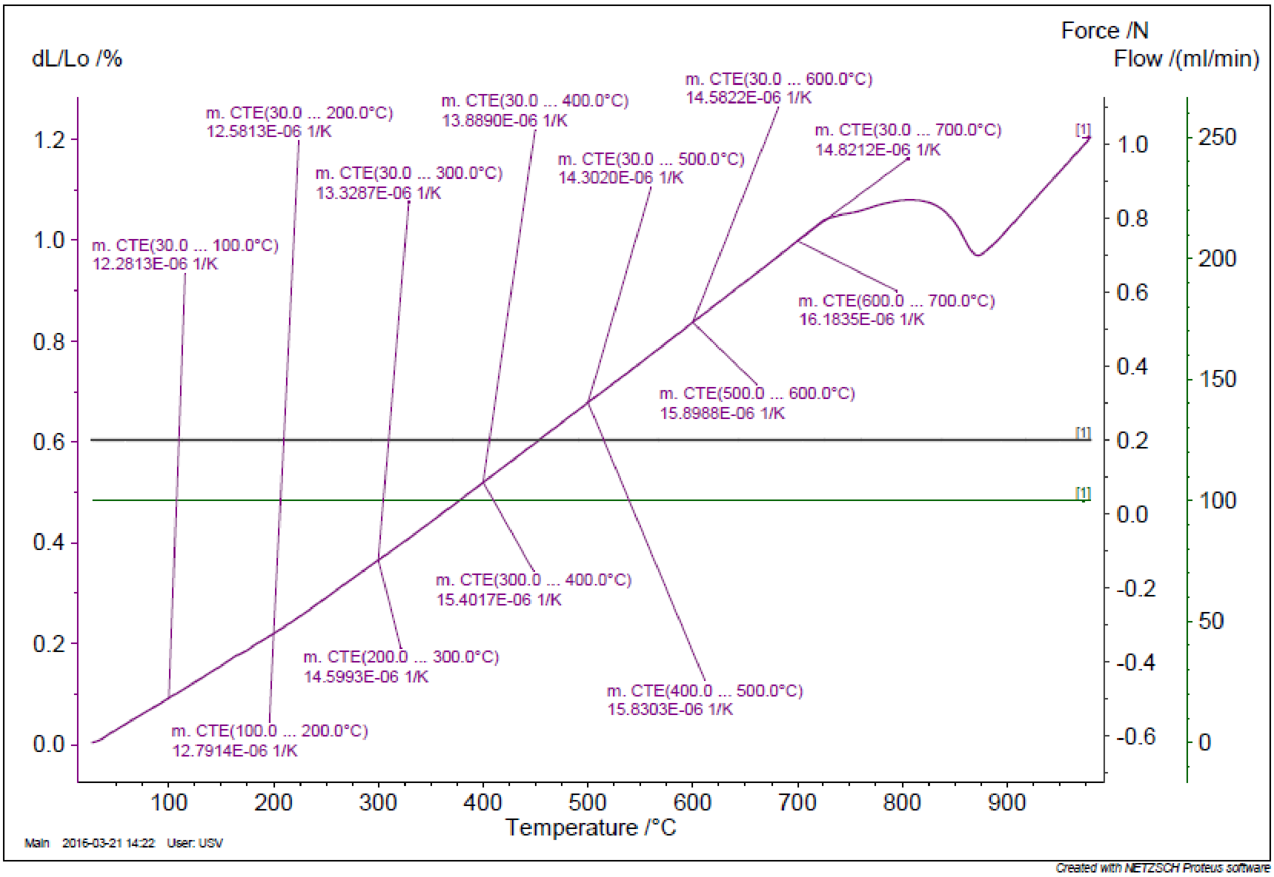

Figure 2: *The dilatometric curve and the coefficient of linear thermal expansion (CTE) for temperature ranges between 30 and 700 ˚C and a heating rate of 3 ˚C/min.*

Table 1: *The coefficient of linear thermal expansion (CTE) in K^{-1}, depending on the heating rate and temperature ranges.*

Heating rate	Temperature range, ˚C						
	30 ÷ 100	30 ÷ 200	30 ÷ 300	30 ÷ 400	30 ÷ 500	30 ÷ 600	30 ÷ 700
1 ˚C/min	$12.4842 \cdot 10^{-6}$	$12.9369 \cdot 10^{-6}$	$13.5605 \cdot 10^{-6}$	$14.0485 \cdot 10^{-6}$	$14.5021 \cdot 10^{-6}$	$14.8031 \cdot 10^{-6}$	$15.0128 \cdot 10^{-6}$
3 ˚C/min	$12.2947 \cdot 10^{-6}$	$12.8444 \cdot 10^{-6}$	$13.4223 \cdot 10^{-6}$	$13.9153 \cdot 10^{-6}$	$14.3413 \cdot 10^{-6}$	$14.6497 \cdot 10^{-6}$	$14.8513 \cdot 10^{-6}$
5 ˚C/min	$12.0058 \cdot 10^{-6}$	$12.7268 \cdot 10^{-6}$	$13.2158 \cdot 10^{-6}$	$13.7978 \cdot 10^{-6}$	$14.1664 \cdot 10^{-6}$	$14.5852 \cdot 10^{-6}$	$14.8339 \cdot 10^{-6}$
10 ˚C/min	$11.1989 \cdot 10^{-6}$	$12.1986 \cdot 10^{-6}$	$13.0040 \cdot 10^{-6}$	$13.6219 \cdot 10^{-6}$	$14.0802 \cdot 10^{-6}$	$14.5046 \cdot 10^{-6}$	$14.8203 \cdot 10^{-6}$
30 ˚C/min	$8.1539 \cdot 10^{-6}$	$11.4013 \cdot 10^{-6}$	$12.6822 \cdot 10^{-6}$	$13.4275 \cdot 10^{-6}$	$13.9641 \cdot 10^{-6}$	$14.4068 \cdot 10^{-6}$	$14.7689 \cdot 10^{-6}$

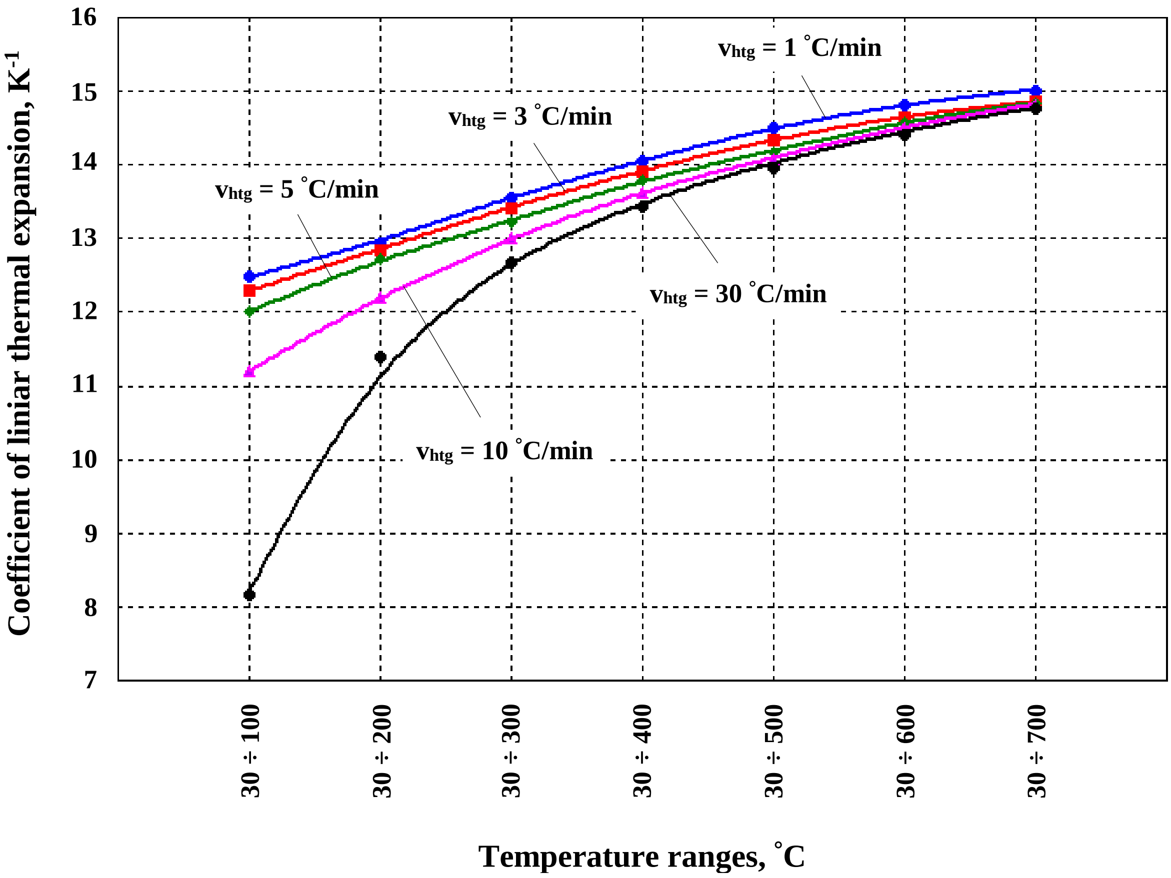

Figure 3: *The variation of the coefficient of linear thermal expansion (CTE) on the heating rate and temperature ranges.*

4. Conclusions

• Thermal expansion is the phenomenon by which the physical dimensions of a body are growing as a result of the change in temperature. For a solid the relative increase of a dimension (the ratio of the change in size and the original size) is proportional with increasing temperature. The coefficient of proportionality is called the coefficient of thermal expansion, a quantity whose unit of measure is the inverse of the temperature unit of measure.

• Determining the coefficient of linear thermal expansion measurement requires two physical quantities, namely the displacement and temperature, for a specimen that is subjected to a thermal cycle. The dilatometric analysis (mechanical dilatometry) is one of the oldest and most commonly used methods to measure thermal expansion.

• Research carried out worldwide in order to obtain and use some dual-phase steels with low content of manganese (less than 1%), have led to a commercial steel with 0.087% C and Mn 0.511% (Si, Cr, Ni, Mo, Al, Cu, V and W under 0.1%) for whom it was established the coefficient of linear thermal expansion (CTE).

• The analysis were performed with a dilatometer DIL Expedis-402 SUPREME on cylindrical specimens (ϕ 5 x 25 mm), heated in 30 ÷ 980 ˚C temperature field, heating with speeds of 1 ˚C/min, 3 ˚C/min, 5 ˚C/min, 10 ˚C/min and 30 ˚C/min, and the coefficient of linear thermal expansion (CTE) was determined for temperatures ranges between 30 and 700 ˚C.

• For the same heating rate, the value of the coefficient of linear thermal expansion (CTE) increased with the temperature; This increase in CTE values was small, uniform and constant in the case of very small heating rates (1 ˚C/min, 3 ˚C/min); for high heating rates (10 ˚C/min, 30 ˚C/min), the CTE values have strongly increased on the first three intervals (30 ÷ 100 ˚C, 30 ÷ 200 ˚C and 30 ÷ 300 ˚C) after which the increasing was much smaller, uniform and constant.

- For the same range of temperatures, the value of the coefficient of linear thermal expansion (CTE) decreased with the heating rate increasing, but this decrease has become less pronounced with the increasing the temperature interval; for 30 ÷ 700 ˚C heating range the CTE values, for all five rates, were almost equalized.

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