The Coefficients of Thermal Expansion of PEX, Brass, Al,

Stainless Steel, 1018 Steel, and Al_2O_3

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Abstract

The objectives of this experiment were to determine and analyze the coefficients of thermal expansion α of different materials, including cross-linked polyethylene (PEX), brass, aluminum (Al), stainless steel, 1018 steel, and alumina (Al_2O_3), using a mechanical dilatometer (Orton manual model 2010 STD). The experiment discussed the origin of thermal expansion and how the magnitude differs for different classes of materials. The findings showed that PEX as a polymer exhibited the largest value due to the weak secondary bonding, and Al_2O_3 as a ceramic presented the lowest value due to the strength of the covalent bonds. Due to metallic bonding, α for metals ranges between α of ceramics and polymers. The coefficients of thermal expansion of PEX and Al_2O_3 , Al, brass and stainless steel were determined to be 327.0×10^{-6} $^oC^{-1}$, 10.0×10^{-6} $^oC^{-1}$,27.0×10^{-6} $^oC^{-1}$, 21.0-$\times10^{-6}$ $^oC^{-1}$ and 21.0×10^{-6} $^oC^{-1}$, respectively. The 1018 steel underwent solid-solid phase transformation from BCC to FCC with α of 16×10^{-6} $^oC^{-1}$ and 23×10^{-6} $^oC^{-1}$, respectively. The findings of the experiment implies that the expansion of materials must be considered when designing structures in engineering applications particularly when large changes in dimension due to temperature are expected.

Introduction

When a substance is heated, the kinetic energy of its atoms increases. Consequently, the atoms start to vibrate and move to a greater average separation. In other words, when temperature increases, the average interatomic separation between atoms increases, and the material expands. [1,2] Thermal expansion is defined as a material property that is indicative of the extent to which a material expands upon heating, and has units of reciprocal temperature. [2]

The origin of thermal expansion is the irregularity of the interatomic potential energy (U) vs. interatomic separation (r) curve as shown in Figure 1a. [1,2] The equilibrium interatomic separation at 0 K occurs near to the minimum of the U vs. r curve. When heat is transferred to the material, interatomic vibrations above the ground state (E_1) are excited. Because the asymmetry of the interatomic potential energy curve is more distinct for larger interatomic distances. the average interatomic distance increases for excited energy levels. However, a symmetrical potential energy curve would result in no thermal expansion due to the fact that there is no change in the average interatomic separation as temperature (energy) increases, as demonstrated in Figure1b. [1,2]

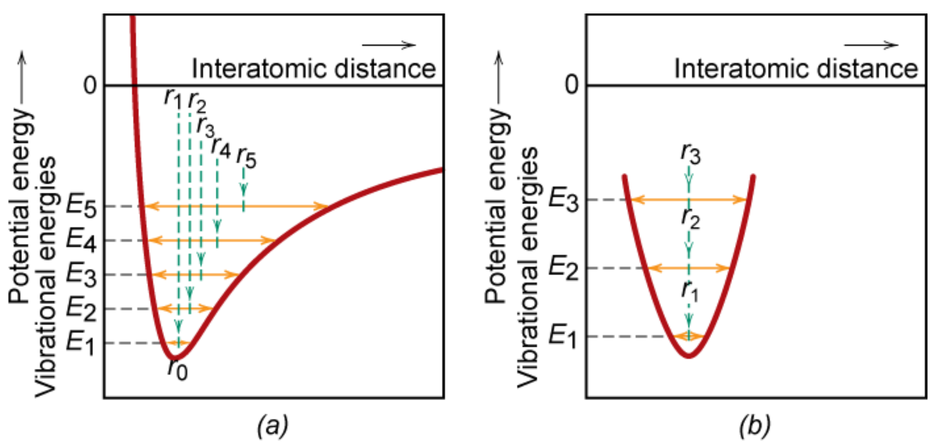

Figure 1. Potential energy versus interatomic separation for materials (a) with and (b) without asymmetry in the potential well. [2]

This behavior can be defined numerically as the coefficient of thermal expansion, α ($^{o}C^{-1}$ or K^{-1}), which is the stress-free strain per unit temperature change. The change in length of a material is thus given by

$$\Delta l/l_o = \alpha\Delta T. \qquad \text{(Equation 1)}$$

where l_o is the initial length, Δl is the change in length and ΔT is the change in temperature.

Since thermal expansion of a material depends upon its interatomic bonding, the coefficient of thermal expansion depends on the class of material. Linear and branched polymers exhibit the largest $\alpha \approx 50\text{-}400 \times 10^{-6}\ ^{o}C^{-1}$, because they have weak secondary bonds.[1,2] It is worthwhile to note that increased degrees of crosslinking result in lower α. Most metals have intermediate bond strengths, giving $\alpha \approx 5\text{-}25 \times 10^{-6}\ ^{o}C^{-1}$. In general, ceramics exhibit strong interatomic bonding, and thus have relatively low $\alpha \approx 0.5\text{-}15 \times 10^{-6}\ ^{o}C^{-1}$.[2,3] Solid-state phase transformations can be easily detected by changes in α at the phase transition temperature.

Thermal expansion can be measured by three main techniques: optical interference, thermomechanical analysis, and mechanical dilatometer.[1] Although optical interference has the best precision and accuracy, it is limited in its temperature range, which is less than that of the mechanical dilatometer (-150 to 2,000 ^{o}C).[1] Thermomechanical analysis is to some extent inconsistent compared to the other techniques.[1] With an expansion dilatometer, the sample length is measured as a function of temperature. A furnace provides sample heating and cooling, and a thermocouple is used for measuring temperature. A linear variable differential transducer converts length changes to voltage (in the mV range), which can then be documented with a computer.[1]

The objectives of this experiment were to determine and analyze the coefficients of thermal expansion of different types of materials, including cross-linked polyethylene (PEX), brass, aluminum (Al), stainless steel, 1018 steel, and alumina (Al_2O_3) using a mechanical dilatometer (model: Orton 2010 STD). Al, brass, stainless steel and 1018 steel are classified as metals whereas Al_2O_3 is classified as a ceramic and PEX as a polymer. [2]

Experimental procedure

In this experiment, the coefficients of thermal expansion of the following materials were measured: cross-linked polyethylene (PEX), brass, aluminum (Al), stainless steel, 1018 steel, and alumina (Al_2O_3). The equipment used was Orton 2010 STD dilatometer. The program used to record and compute the measured values was Orton 5.2.1 Industrial Software. The measurements were taken at 1 atm.

First, the initial length of each sample was measured using a dial Vernier caliper. Then, each sample was mounted into the dilatometer between the end of the sample holder and the end of the movable probe rod. A load was attached to the sample by the pulley system in order to assure that the sample was in a good contact to accurately measure the expansion. After that, the furnace was slidden over the sample. The result value was adjusted by rotating the nope to 0.10 for calibration. A heating rate of 3 ^{o}C/min was used for the PEX sample and of 20 ^{o}C/min was used for all other samples. The temperature range over which to measure each sample and the initial length measured are summarized in Table 1. The initial length of the sample and the temperature range were entered into the software. The % linear expansion as a function of temperature for the different materials was measured. The software collected and displayed time, temperature, and percent linear change data, and stored it in a binary file. Data for 1018 steel was given in the course locker. Graphs were generated and slops were calculated using Excel.

Table 1. Initial lengths and temperature ranges for measurements of *α*.

Sample	The initial length (inch)	Temperature Range (ºC)
PEX	1.074	30-100
Al	0.999	150-400
Brass	0.997	300-550
Stainless Steel	1.015	500-750
1018 Steel	-	600-1000
Alumina	1.001	650-900

Al is a pure metal. Brass is a metal alloy composed of 70% copper and 30% zinc. Stainless steel contains iron with 12–14% chromium, 0.2–1% molybdenum, less than 2% of nickel and 0.1–1% carbon. The chemical composition of 1018 steel is iron with 0.15-0.20% carbon, 0.60-0.90 % manganese, less than 0.05% of Sulfur and 0.04% of phosphorous. Alumina is a ceramic combining 40% aluminum and 60% oxygen. PEX is made from high-density polyethylene (HDPE). [2,3,4]

Results and Discussion

In order to determine the coefficient of linear thermal expansion for each sample, the % linear expansion versus temperature curves were plotted as shown in Figure 2. It was obvious from these curves that different materials expand at different rates when heated. It was observed PEX sample exhibited the steepest slope, a very rapid expansion, whereas alumina exhibited the flattest slope, a very slow expansion. The slop of the PEX curve was not as linear as the other samples' slopes. The slopes of Al, brass, stainless steel and 1018 steel were found to be in between the slops of PEX and alumina. When comparing metals, Al was found to have the largest slop, indicating that it expanded faster the other metals. Moreover, the 1018 steel sample showed a change in slope. When heated, it continued to expand with a positive slope until it reached a temperature of about 750°C, where it began to shrink with a negative slop while still being heated. The shrinking of 1018 steel continued until it reached a temperature of about 850°C, above which temperature the steel began to expand once again, as illustrated in Figure 2.

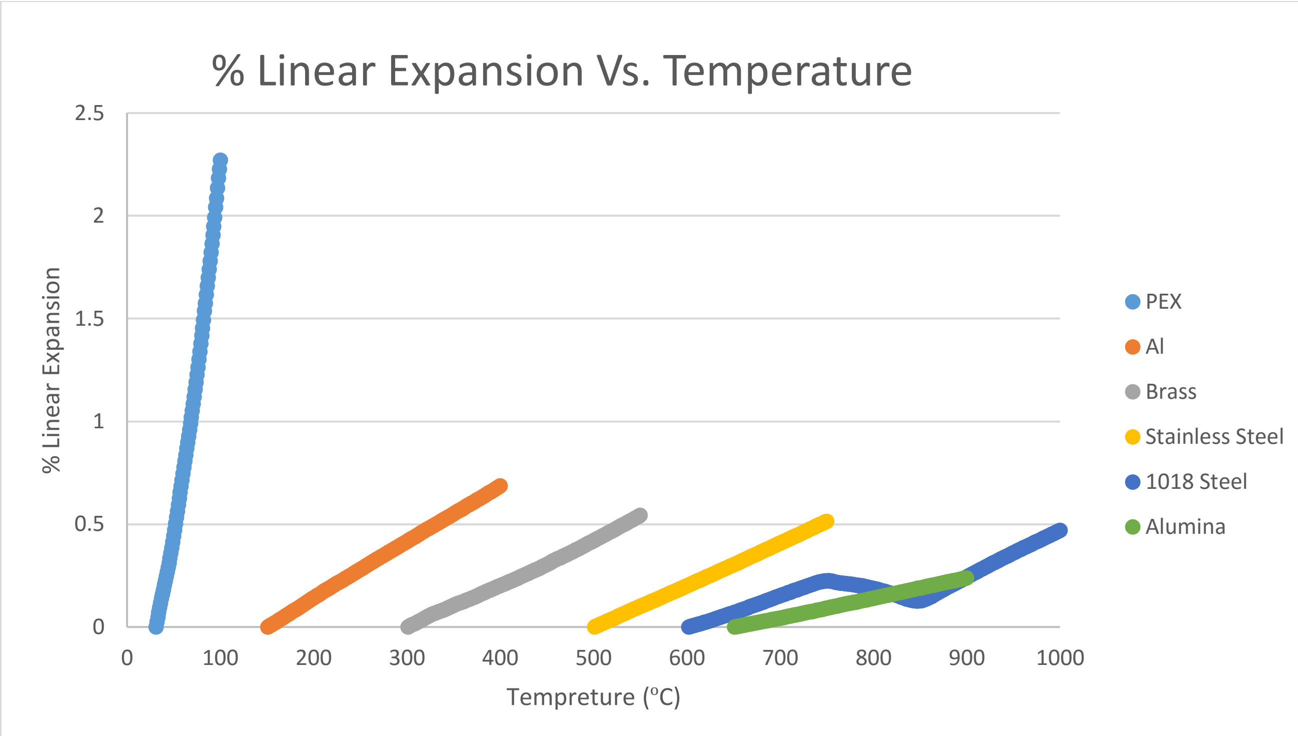

Figure 2. The % linear expansion as a function of temperature for PEX, brass, Al, stainless steel, 1018 steel, and alumina.

Given Equation 1 and Figure 2, the thermal expansion coefficients were calculated by finding the slop as linear fit in Excel and dividing it by 100. The coefficients of thermal expansion of PEX and Al_2O_3 were determined to be 327.0×10^{-6} °C^{-1} and 10.0×10^{-6} °C^{-1} respectively. The coefficients of thermal expansion of Al, brass and stainless steel were determined to be 27.0×10^{-6} °C^{-1}, $21.0\text{-}\times10^{-6}$ °C^{-1} and 21.0×10^{-6} °C^{-1}, respectively. For 1018 steel, the first slope was found to be 16×10^{-6} °C^{-1} and the second slope was found to be 23×10^{-6} °C^{-1}. Table 2 summarizes the measured thermal expansion coefficients, the literature values and the % difference between the two values. The % difference is calculated as the difference between two values divided by the average of the two values. A sample calculation of the % difference is shown as the following:

$$\%\,difference\ of\ Al = \frac{27.0 - 23.6}{\left(\frac{27 + 23.6}{2}\right)} \times 100 = 13.438\,\%$$

Table 2. Measured thermal expansion coefficients α in comparison to the literature values.

Sample	Measured α (1/ºC) × 10^{-6}	literature value (1/ºC) × 10^{-6}	% difference (%)
PEX	327	198	49.142
Al	27.0	23.6	13.438
Brass	21.0	20.0	4.878
Stainless Steel	21.0	16.0	27.027
1018 Steel	16.0	12.4	25.350
Alumina	10.0	7.6	27.27

As indicated by the coefficients of thermal expansion, PEX as a polymeric material experienced very large thermal expansions upon heating due to the weak secondary intermolecular bonds, which additionally resulted in a non-linear curve. It is worthwhile to note that with increased crosslinking, the strength of the interatomic bonds increases and the magnitude of the expansion coefficient reduces.[2] In contrast, Al_2O_3 as a ceramic material presented a low coefficient of thermal expansion due to the strong covalent and ionic interatomic bonding forces.[1,2]

For Al, brass, stainless steel and 1018 steel as metals, linear coefficients of thermal expansion were found to be intermediate in magnitude between those for ceramic and polymeric materials due to the fact that metallic bonds are stronger than secondary bonds and weaker than covalent and ionic bonds.[2] Al presented the largest α in metals because it has identical atoms arranged in regular layers, where they can slide over each other easily.[2,3] In contrast, brass and steel are composed of different-sized atoms of the mixed metals, which makes the atomic layers less regular, so they cannot slide as easily.[2] Consequently, metal alloys are stronger and harder than pure metals and therefore exhibit smaller coefficients of thermal expansion.

This strange behavior of 1018 steel when heated is due the fact that iron changes from one crystallographic arrangement of atoms to another.[1,2] By analyzing the iron-iron carbide phase diagram, the iron in 1018 steel at room temperature exhibit the alpha-iron(ferrite) phase, which has a BCC crystal structure until it reaches about 750°C.[2] It changes to gamma-iron (austenite), which has an FCC crystal structure, when heated to above approximately 850°C, as shown in Figure 2.[2] While changing from a BCC to an FCC crystal structure during heating, reduction of the metal lattice structure is caused by the heat absorbed during the phase change and the efficiency of the packing of atoms in FCC, allowing more iron atoms to fit in a given space than in the BCC alignment.[2,3] BCC structure is more brittle and stronger than FCC structure and thus has a lower coefficient of thermal expansion than FCC, which agreed with the measured slops for 1018 steel.[2,3]

In general, these results agree with the reported values found in literature.[2,4] Variations between the measured values and the literature values of the coefficients of thermal expansion can be explained by the following factors. First, the heating rate used was slightly high. Second, the samples examined might have some significant defects and vacancies. Third, the orientations of the samples when placed in the dilatometer might be slightly off.

Conclusions

The objectives of this experiment were to determine and analyze the coefficients of thermal expansion α of different types of materials, including cross-linked polyethylene (PEX), brass, aluminum (Al), stainless steel, 1018 steel, and alumina (Al_2O_3) using a mechanical dilatometer (model: Orton 2010 STD). Al, brass, stainless steel and 1018 steel are classified as metals whereas Al_2O_3 is classified as a ceramic and PEX as a polymer.

Overall, the experiment was successful in showing that with increased strength of the interatomic bonds and bond energy, the coefficient of thermal expansion of a material decreases. The coefficients of thermal expansion of PEX and Al_2O_3 , Al, brass and stainless steel were determined to be 327.0×10^{-6} $^oC^{-1}$, 10.0×10^{-6} $^oC^{-1}$,27.0×10^{-6} $^oC^{-1}$, 21.0-$\times10^{-6}$ $^oC^{-1}$ and 21.0×10^{-6} $^oC^{-1}$, respectively. The 1018 steel underwent solid-solid phase transformation from BCC to FCC with α of 16×10^{-6} $^oC^{-1}$ and 23×10^{-6} $^oC^{-1}$, respectively. The experiment suggested that polymers exhibit the largest α due to the weak secondary bonding and ceramics exhibit the lowest α due to the strong covalent bonding, while α range in metals falls in between the two classes of materials due to the metallic bonding. [2,3]

The experiment suggested that harder materials such as metal alloys when compared to pure metals are more likely to have lower thermal expansion. Furthermore, the fact that different materials exhibit different rate of expansion implies that the expansion of materials must be considered when designing structures in engineering applications particularly when large changes in dimension due to temperature are expected. [3]

References

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