From fundamental principles to mechanics near absolute zero

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KEYWORDS: *Cryogenics, Weakly Excited Lattice, Dissipative Phenomena, Fundamental Principles.*

Cryogenics was born in Kraków in 1883, when Karol Olszewski, an outstanding chemist, carried out – together with the physicist Zygmunt Wróblewski – the first successful liquefaction of air. Nowadays, attaining temperatures close to absolute zero is relatively standard, although it still requires sophisticated and complex equipment. In the vicinity of absolute zero, the thermal conductivity, thermal expansion coefficient, and specific heat of metals and their alloys all tend toward zero. This behaviour is fully consistent with the third law of thermodynamics, which states that the entropy of a perfect crystal at absolute zero is equal to zero. It is well known that heat transport in a crystal lattice is governed by two fundamental mechanisms: phonon transport and free-electron transport. At extremely low temperatures, the contribution of lattice quantum vibrations (phonons) is limited to acoustic modes and can be described as the total energy of the lattice, represented by the sum of the energies of all harmonic oscillators. The excess lattice energy above zero vibrations is proportional to the fourth power of temperature; consequently, the specific heat – expressed as the derivative of lattice energy with respect to temperature – is proportional to the third power of temperature. As the specific heat approaches zero with decreasing temperature, the derivative of temperature with respect to heat (dT/dQ) tends to infinity. Therefore, near absolute zero, even an arbitrarily small dissipation of energy can produce a significant increase in temperature. In the present paper, several dissipative phenomena occurring in crystal lattice at very low temperatures are discussed, including intermittent plastic flow [1], plastic strain–induced phase transformations, the evolution of microdamage, fracture [2], as well as creep mechanisms. Intermittent plastic flow represents an oscillatory mode of plastic deformation that occurs below a critical temperature: T_0 for materials with high stacking fault energy (HSFE) and T_1 for materials with low stacking fault energy (LSFE). Plastic flow in metastable materials, such as stainless steels, at extremely low temperatures is usually accompanied by a dynamic evolution of the microstructure resulting from plastic strain–induced fcc–bcc phase transformation. Ductile damage and fracture are key issues for metastable materials operating at extremely low temperatures. A broad class of these materials, particularly stainless steels, exhibits clear evidence of ductile fracture. Moreover, extensive studies of the long-term creep behaviour of metals and alloys at cryogenic temperatures clearly indicate that creep occurs even at temperatures approaching absolute zero (liquid helium, 4.2 K). To explain the background of these phenomena, the behaviour of liquid and superfluid helium – the only element that remains in a liquid state down to absolute zero – is examined, with particular emphasis on phase transitions. Heat transport across the solid–fluid boundary and its influence on lattice-related dissipative phenomena are also illustrated and discussed. All of these effects are considered in the context of the fundamental principles of mechanics and thermodynamics.

ACKNOWLEDGEMENT: Project of the National Science Centre 2021/41/B/ST8/01284 is acknowledged.

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