Chapter 1
Engineering Problems Related to "Thermal Engineering"

1. Introduction

So far, the academic field of "Thermal Engineering" is involving "Combustion Engineering" in which effective generation of thermal energy from the chemical potential of "fuels" is examined, "Thermodynamics" which is the basic theory for conversion of thermal energy into mechanical work, "Heat Transfer" in which the "rate" of thermal energy transfer is discussed, and "Thermo-physical Properties" examining physical properties of the materials used in the thermal engineering field. This construction of the "Thermal Engineering" corresponds to the way for developing heat engines having high power output and/or heat transfer equipment, e.g. heat exchangers for air-conditioner, of high efficiency. As the industrial products are sophisticated, however, the level of requirement from the application field for thermal engineering becomes higher. Consequently the room for expanding the idea becomes highly restricted, and the researchers/engineers in the thermal engineering field are forced to work in the "background."

Under the situation, many researchers in the thermal engineering field are now trying to find out the cutting-edge of application, so as to spread the field in which their ideas are applicable, and to take the initiative in progress in this field. In this lecture, taking illustrations from the state-of-the-art of thermal engineering applied for the engineering problems, the challenge of these researchers and their viewpoint will be discussed.

2. Results of Thermal Engineering in Old Paradigm

Prior to the discussion about the challenge of researchers in thermal engineering, let us discuss some results of thermal engineering in old paradigm, i.e. thermal engineering applied for managing thermal energy in the sophisticated industrial products. Most typical example of the results of thermal engineering application would be cooling of electronic device in Notebook PCs (Personal Computers), size and weight of which are rapidly reduced recently.

The MPUs (Micro Processing Units) of the up-to-date PCs tend to be operated at higher clock frequency with higher voltage power supply, so as to improve processing speed. Since consumption of electric power in the MPUs is in proportion to the square of voltage supplied and the clock frequency, heat generation within the MPUs increases very rapidly. 10 years ago, power consumption of the MPUs was about 2 W, but nowadays it reaches more than 30 W. On the other hand, the size of bare chip of the MPUs is about $10 \times 10\ \mathrm{mm}^2$, and it cannot be increased so much, since the processing speed of the MPUs is in inverse proportion to the length of wiring in the bare chip. Namely heat flux radiated from the bare chip is about $30\ \mathrm{W/cm}^2$, which is 10 times larger than the heat flux at the bottom of kettle heated with an electric heater of 1 kW. In order to keep the chip sound, therefore, cooling of MPU is keenly required.

Such a kind of problem arises on the CPUs (Central Processing Units) of Mainframe computers. In the Mainframe computers, the CPUs are sometimes immersed in a low boiling-point liquid, and are cooled by utilizing boiling heat transfer. However, for the MPU in Notebook PCs, it is difficult to apply such a complicated cooling system due to limitation of size and power consumption. In the Notebook PCs, therefore, "air-cooling" is often used for cooling the MPU.

Because of the limited cooling capability of "air-cooling," and because of the high-density packaging of electronic devices in the up-to-date Notebook PCs, it is required to develop high-efficiency extended-surface for heat transfer, in order to apply the "air-cooling" for cooling of MPU in the Notebook PCs. For this purpose, knowledge of thermal engineering has been applied. For example, MPU in some Notebook PCs has a heat sink with "heat pipes" (see Figures 1.1 and 1.2). The heat pipe is a thermal device having an ultimately high apparent thermal conductivity, and thus, by using this device, heat generated at the MPU, which is usually placed near the center of motherboard, can be efficiently transferred to the heat sink having large heat transfer area even if the cross section of the heat pipe is quite small. Such kinds of thermal devices are the typical fruits of thermal engineering, and are the pride of us, researchers in thermal engineering field, since smaller PCs of higher performance can not be developed any longer without the knowledge of thermal engineering.

Figure 1.1 Heat sink for MPU with a heat pipe[1].

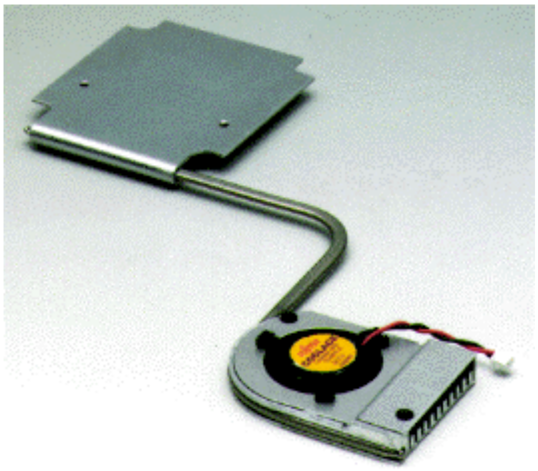

Figure 1.2 MPU cooler with a heat pipe[2].

However, we, researchers in thermal engineering field, are never being satisfied with the current situation of thermal engineering. Indeed thermal engineering is one of the keys of the innovative products, such as the high performance Notebook PCs, and until 2 or 3 decades ago thermal engineering dominated the whole products. But nowadays the researchers in thermal engineering field in old paradigm are not possible to be a "creator" of the whole products.

3. Thermal Engineering in New Paradigm

Under the situation, we are trying to make new paradigm of the thermal engineering. The new paradigm consists of the following three parts:

(a) Accumulation of knowledge of thermal engineering; as the advance of the thermal engineering in old paradigm, engineering knowledge applicable for designing the industrial products is accumulated continuously.

(b) Study on the physical aspects of thermal engineering; in order to understand the principle of thermophysical phenomena, the phenomena are studied from the physical point of view. So-called MD (Molecular-Dynamics) simulation of the thermophysical phenomena comes under this category.

(c) Searching the new application fields in which thermal engineering plays a major part; combining the knowledge obtained so far, application field of thermal engineering is searched so as to develop industrial products having novel functions.

These parts of thermal engineering in new paradigm compensate with each other so as to expand the possibility of thermal engineering.

4. Objective of This Lecture

In this lecture, I will lecture to you the concept of part (c) of the aforementioned new paradigm of thermal engineering. Part (a) and part (b) are still "analysis" of the phenomena, but the part (c) is not "analysis" but "synthesis" of knowledge for the application field. Therefore part (c) of the new paradigm requires the way of thinking differ from that for part (a) or part (b): not only the effort but also the "idea" of researcher dominate the success of this part. This is the key of the lecture.

I will discuss the "way of thinking" in synthetic research, taking illustrations from the thermal engineering applied for manufacturing processes.

References

[1] WWW site of Furukawa Electric Co.: http://www.furukawa.co.jp/what/hinji.htm
[2] WWW site of Fujitsu Co.: http://www.fujitsu.co.jp/hypertext/news/1998/Mar/18.html

Chapter 2
Thermal Engineering in Manufacturing Processes

1. Manufacturing and Productivity

In general, final objective of engineering is, directly or indirectly, to plan, to design and to manufacture "things." In particular, mechanical engineering is strongly related to "making things," especially making hardware.

Method and process of the manufacturing part of "making things" including planning and designing are called as "Manufacturing Process." The manufacturing process consists of machining such as casting, drawing, milling, grinding, etc., fabrication including welding, adhesion, screwing, riveting of parts, and decoration/treatment such as painting, plating, etc. In the practical manufacturing, these processes are closely combined with each other. On the other hand, the "things" made by the manufacturing process are including the materials, e.g. Si crystal for electronic devices, and the parts of industrial products, not to mention the sophisticated products such as automobiles and computers. And not only "mass production" but also "craftwork" is the target of the manufacturing processes.

The most typical feature of the manufacturing process for mass production is that the "productivity" takes priority over everything. Production of high-quality and/or highly functional products requires a certain amount of time and effort. Time required for manufacturing reflects directly the cost of products, and thus faster production, i.e. manufacturing process with higher productivity, is more advantageous if the products have the same quality and functions. Certainly the manufacturing processes used in the practical production are well refined from the viewpoint of productivity in general. So when one wants to propose a novel manufacturing process or an improvement of the existing manufacturing processes, one should take its impact on the productivity into consideration. It would be quite difficult for the researchers in universities, who do not have actual products the cost should be spend for.

2. Manufacturing Processes with Heat Transfer

Major part of the manufacturing process, including material processing and fabrication of parts, is related to heat transfer. In particular, manufacturing processes, in which functions are added to the materials by changing its shape and/or properties, are strongly related to the heat transfer phenomena.

Heat transfer in the manufacturing process can be classified into the following two categories.

(1) Passive heating/active cooling: During the manufacturing process, deformation of materials and/or friction between the materials and tools may result in automatic generation of heat (passive heating of materials). When the temperature rise due to the heat generation is not preferable for the products, the material (and the tool as well) should be cooled by some means (active cooling).

(2) Active heating/active cooling: During the manufacturing process, thermal energy is poured into the materials so as to rise their temperature (active heating) at first, some operations are done for the materials, and then the materials are cooled down to the ambient temperature (active cooling). The reason why the materials are heated before operation is, in general, shape and properties of most of all materials can be changed more easily at higher temperature. In some case, the materials are cooled before operation so as to make the properties of materials suitable for the operation, and then the materials are heated upto the ambient temperature. This cooling/heating process belongs to the category as well.

From the practical point of view, heat transfer in the former category is important in the precise operation, such as high-precision machining of metals, since deformation of work (material) and tool due to their temperature change affects the accuracy of products. Therefore active cooling (or active temperature control) of work and tool is essential for the up-to-date precise machining. However this kind of heat transfer is not interesting to us, the researchers in thermal engineering field, because in this case only the efficient cooling is required to maintain the temperature of work and tool. On the other hand, control of the heat transfer in the latter category could be attractive for us, since temperature history of the material and the phenomena occurring due to the heating/cooling affect the quality, accuracy and functions of the products as well as the productivity of the process, and thus the heat transfer could play the leading role in the manufacturing processes. In this lecture, therefore, I will discuss the "way of thinking" in synthetic research, taking illustrations from the heat transfer control in the latter category.

3. Heat Transfer in Melting Processing

The most typical manufacturing process in which the heat transfer of category (2) takes place is the Melting Processing. In the melting processing, the material is melted by heating first, formed into a certain shape by adding forces or by joining other materials, and then is solidified by cooling the material so as to fix the shape. Or changes of physical properties of the material due to the heating/cooling process are utilized as the function of products. In practice, the melting processing involves the following manufacturing processes/methods:

(a) Casting of metals, including die-casting (Figure 2.1)
(b) Polymer processing, including film casting and fiber drawing (Figure 2.2)
(c) Welding and melt-cutting (Figure 2.3)
(d) Single-crystal growth of semiconductor materials (Figure 2.4)

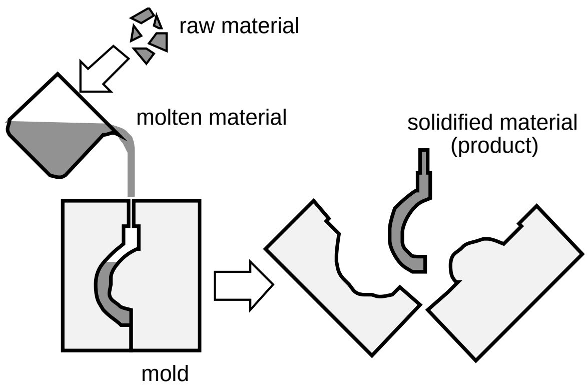

Figure 2.1 Casting of metals.

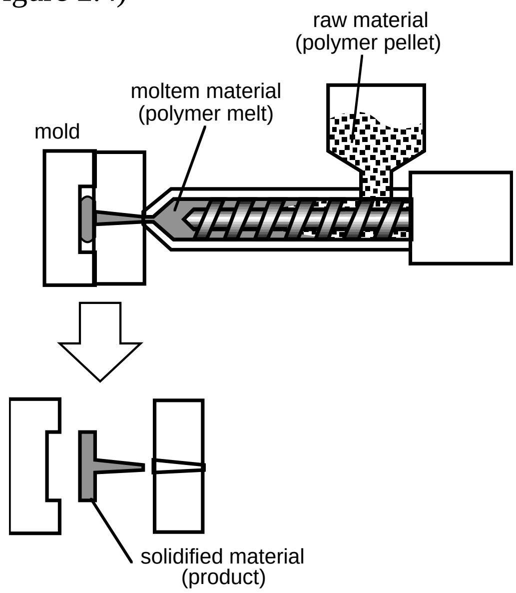

Figure 2.2 Polymer processing (injection molding).

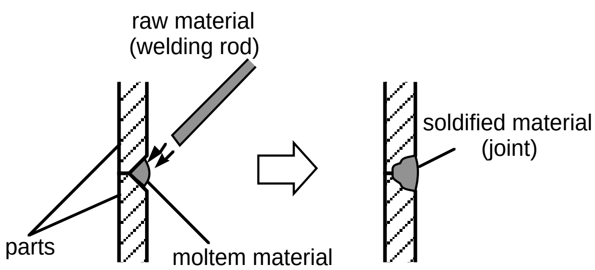

Figure 2.3 Welding.

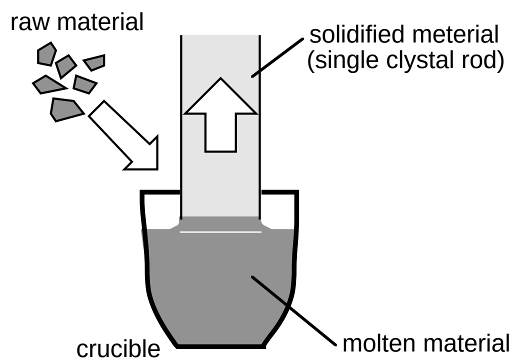

Figure 2.4 Single-crystal growth process.

In order to improve productivity of these melting processes, it is necessary to reduce the time required for heating/cooling of the materials. The reduction of time required for heating/cooling can be achieved by (1) increasing area of heat transfer surface, i.e. surface area of material being touch with the heating/cooling medium, (2) increasing temperature difference between the material and heating/cooling media, i.e. using higher temperature heating medium and/or lower temperature cooling medium, and (3) enhancing heat transfer on the surface of materials. These measures for heat transfer enhancement are quite common for the researchers/engineers in the thermal engineering field, and therefore there is no difficulty to achieve quicker heating/cooling. However, in manufacturing processes for some materials such as alloys and polymers, properties of the products are often affected by the temperature history during the processing. In such processing, heating/cooling rate of the material is limited by the properties of products appearing in the heating/cooling processes, and the productivity, i.e. heating/cooling rate of the materials, has to be compromised with the quality/functions of the products.

In addition, effectiveness of the thermal energy utilization should be taken into consideration as well. Theoretically speaking, melting processing does not consume thermal energy, because amount of energy poured into the material during melting process is identical to the one drawn from the material during solidification process. Actually, however, the energy recovered from the material during cooling process cannot be used as the heating energy again. This is because the heat transfer at finite rate requires temperature difference between the material and heat source/sink. So, it can be said that the melting processing consumes "exergy*" not "energy." In order to reduce the exergy consumption, it is needed to reduce the heating/cooling rate. Namely the productivity has to be compromised also with the exergy consumption in the process.

Figure 2.5 shows the concept of melting processing from the viewpoint of heat transfer. As shown in this figure, heat transfer during the processing affects many things including the quality of products and the productivity of the process. This means that control of the heat transfer can dominate the processing. Next time, I will discuss about details of the heat transfer control in the practical melting processing, e.g. polymer processing.

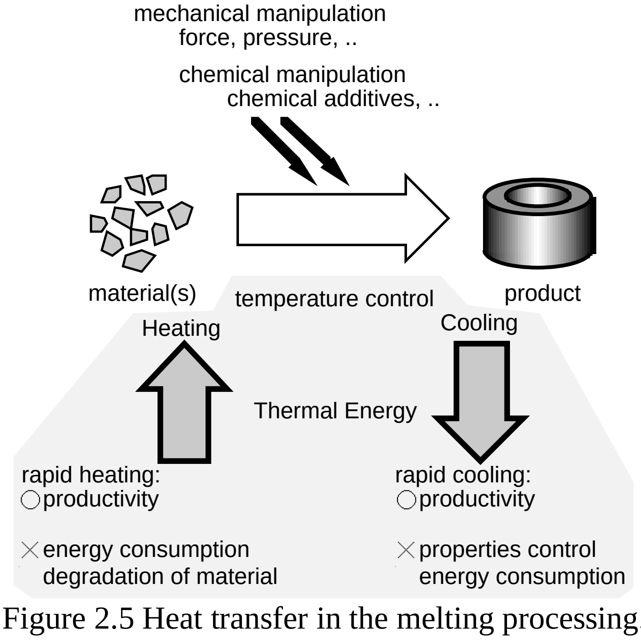

Figure 2.5 Heat transfer in the melting processing.

* About the exergy, see Appendix.

Appendix: What is the "exergy?"

Excergy is also called as "Available Energy," and is the maximum amount of work drawable from the energy source. If the form of energy source is "thermal energy," amount of work L drawable from it is

$$L = \eta Q_1 \tag{2.1}$$

where η is the efficiency of heat engine used to convert the thermal energy to work, and Q_1 is the amount of thermal energy poured into the heat engine. The efficiency of heat engine is at the maximum if the heat engine is an ideal cycle, i.e. Carnot cycle, and the amount of work L_c drawable by using Carnot cycle is

$$L_c = Q_1 \eta_c = Q_1 \left(1 - \frac{T_2}{T_1}\right) \tag{2.2}$$

where η_c is efficiency of Carnot cycle, and T_1 and T_2 are the temperatures of energy source and heat sink, respectively. On the Earth, the minimum value of the temperature T_2 of heat sink is the ambient temperature, and is about 300 K. Consequently the exergy E of thermal energy is the function of its temperature T_1:

$$E(T_1) = Q_1 \left(1 - \frac{T_{amb}}{T_1}\right) \tag{2.3}$$

This means that the "quality" of thermal energy depends on its temperature, and that heat transfer at a finite rate, which requires a finite temperature difference between the heat source and heat sink, consumes exergy.

Problem

Suppose a practical melting processing, and research its temperature conditions, i.e. temperature of heat source, melting and solidification temperature of material, temperature of heat sink, etc. And then, estimate the increase of exergy loss due to heat transfer, when the heat transfer rate is being doubled by doubling temperature difference between the heat source and the material, or between the material and the heat sink.