# Preliminary Application of Reductionism and Holism in Teaching Mechanical Engineering Materials

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**Abstract.** In teaching a key curriculum, Mechanical Engineering Materials, in the discipline of mechanical engineering, reductionism and holism were applied. Besides the calculation of atomic packing factor, three key knowledge points were abstracted by applying reductionism, which were the model on bonding forces and energies of two isolated atoms, diffusion theory, and minimum-energy principle. Basing on these three key knowledge points, plenty of the contents in this curriculum can be understood easily and the learning efficiency can be elevated. Moreover, due to the deficiency of reductionism in analyzing complex issues, such as the influence of electric current stressing on the strength of materials and the ductile-to-brittle transition of a structure at low temperature, holism was applied concurrently. These applications can not only improve the teaching efficiency under a curriculum time shrinking condition, but also show students how to analyze complex issues.

**Keywords:** Reductionism · Holism · Mechanical Engineering Materials

## 1 Introduction

Mechanical Engineering Materials is a mandatory course in college for students in Mechanical Engineering, which is arranged in the second semester of sophomore year. In the sophomore year, the students are required to attend some technical courses. The difference between the technical courses and foundation course compels students to adjust their cognitive mode and problem-solving methodology [2]. While, most students prefer to study this course, Mechanical Engineering Materials, in a traditional route. At the same time, though the teachers possess abundant knowledge in this area, while they also usually teach in a spoon-fed way. This mismatch in cognitive mode and problem-solving methodology between students and teacher causes low efficiency in learning and teaching.

Moreover, the curriculum time of this course is shortened sharply in recent years. While, the requirements remain almost unchanged. In order to achieve the course goals in the limited time, plenty of methods have been used in teaching, such as flip-class, SPOC,


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MOOC, Rain class, etc. Indeed, these methods are attractive and can contribute the seeming elevation of students' course performance. While, this does not mean students have understood the taught contents. Besides, these simplified and entertainment-containing teaching methods can hardly guide student to think independently and critically, which is especially true in the technical courses. In contrast, a domestic teaching paradigm innovated in China, Presentation-Assimilation-Discussion (PAD) class [10], is suitable for Chinese students, and it asks both students and teachers to think deeply after the class, which should be a sound method to improve the learning and teaching performances [6] and a feasible route to fostering independent characters. While, how can both students and teachers think in a similar, high-efficient and inspiring mode? This remained issue asks for a more fundamental thinking route.

Among the various thinking routes, both reductionism and holism are two primary and essential cognitive modes, which are widely used and discussed comparably [7, 8]. Some trials were also conducted in engineering education, and the results were inspiring and enlightening [5]. The concurrent application of reductionism and holism was appealed. Therefore, both reduction and holism were applied in teaching Mechanical Engineering Materials, which were detailed in this paper.

## 2 Application of Reductionism

Since most of the previous scientific progress was achieved basing on reductionism. Though, plenty of teachers do not understand reductionism clearly and deeply, they usually get used to applied reductionism in the teaching. The textbook is also complied in the route of reductionism. For example, the method of breaking down complex concept or knowledge into simple easy-understanding points is widely used in analyzing questions and presenting knowledge, which is reductionism. Similarly, reductionism can also be applied in teaching Mechanical Engineering Materials.

### 2.1 The Application of Reductionism in the Calculation of Atomic Packing Factor of FCC and HCP

Atomic packing factor (APF) is an important parameter in Mechanical Engineering Materials. The face-centered cubic (FCC) crystal structure and the hexagonal close-packed (HCP) crystal structure are two basic crystal structures [1], as illustrated in Fig. 1(a) and (b), respectively. In order to calculate the APF of these two crystal structures, the following equation can be used,

$$\mathrm{APF} = \frac{volume\ of\ \ atoms\ in\ a\ unit\ cell}{total\ unit\ cell\ volume} \tag{1}$$

According to Eq. (1), the APF of FCC crystal structure can be obtained easily due to its simple geometric configuration (see Fig. 1(a2), which is 0.74. While, the calculation is time-consuming for the HCP crystal structure due to its complex geometric configuration (see Fig. 1(b2)). While, it is worth mention that the lattice structure (i.e., the reduced-sphere unit cell) of crystal structure is a simplified model to illustrate the atomic arrangements. Once the atomic arrangements of FCC and HCP crystal structures

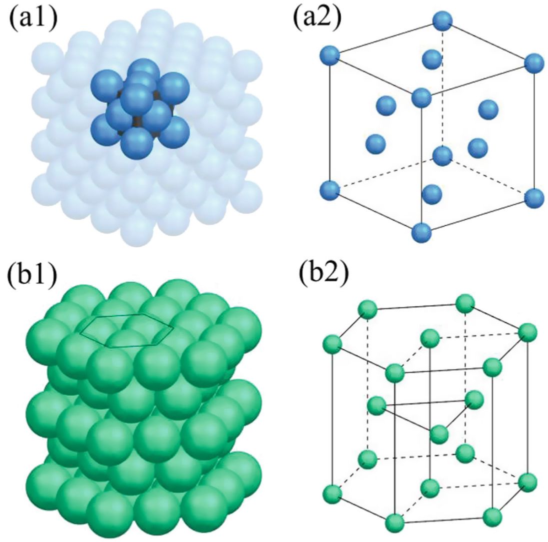


**Fig. 1.** For the FCC crystal structure (a1) an aggregate of many atoms, (a2) a reduced-sphere unit cell; for the HCP crystal structure (b1) an aggregate of many atoms, (b2) a reduced-sphere unit cell

are compared, it is not difficult of find that the atoms are arranged in a same density, and the main difference is that the atoms are packed repeatedly every three layers for the FCC crystal structure while those are every two layers for the HCP crystal structure. Basing on reductionism, it is easy to judge without calculation that the APF of HCP crystal structure is same with that of FCC crystal structure. Clearly, the application of reduction in the calculation of APF of HCP crystal structure is time-saving.

## 2.2 Three Key Knowledge Points of the Curriculum Abstracted Basing on Reductionism

Besides the routine application of reductionism in teaching every chapter of the textbook, three key knowledge points were abstracted as fundamental pillars of the whole knowledge system of the textbook. These three key knowledge points are as following: (1) point 1, the model on bonding forces and energies of two isolated atoms, see Fig. 2; (2) point 2, diffusion theory; (3) point 3, minimum-energy principle. Basing on these three knowledge points, most of the content in this curriculum can be understood easily. Several examples can be shown to prove this inference.

### 2.2.1 The Application of the Three Key Knowledge Points in Understanding the Properties of Grain Interface

One of the example is the application of three key knowledge points in understanding the properties of grain interface. The grain interface is an important planar defect in materials, which shows various properties. These properties include (1) the atomic arrangements

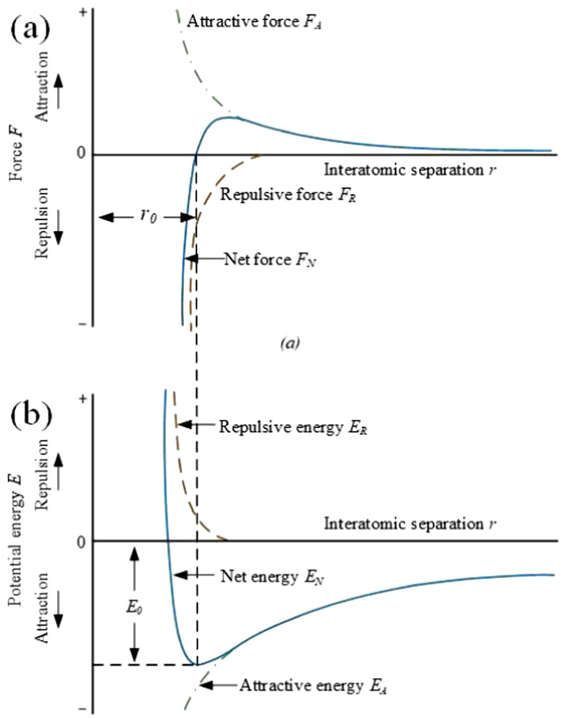


**Fig. 2.** The model on bonding forces and energies of two isolated atoms

at the grain interface are disorderly, (2) the melting temperature at the grain interface is lower than that in the matrix of materials, (3) the corrosion resistance at the grain interface is lower than that in the matrix of materials, (4) the external atom is easy to segregate at the grain interface, (5) the dislocation movement can be impeded by the grain interface, (6) the grain interface is usually the nucleation site of phase transformation. The properties usually can not be understood efficiently by students without reductionism.

To understand the first property of grain interface, reductionism could be applied basing on the nucleation of grains in materials. Since the nucleation site of each grain is different, the various grain orientation usually results in the mismatch of atomic arrangement at the grain interface. Basing on point 1 of the three key knowledge points, it is easy to understand that the net force at the grain interface is lower than that in the matrix of materials due to the larger interatomic distance ($>r_0$). The melting state of materials means the break-down of atomic arrangements. The first property of grain interface indicates that the atomic arrangement at the grain interface is closer to the melting state than that in the matrix of materials, which results in the second property of grain interface consequently. Similar to the analysis of second property, the third property of grain interface can also be understood basing on point 1 of the three key knowledge points. A high corrosion resistance means the lattice structure of materials can not be disrupted easily. While, the lattice structure at the grain interface has been disrupted yet. Accordingly, the corrosion resistance at the grain interface is lower. Besides utilizing point 1 of the three key knowledge points, since the diffusion rate is higher at the grain interface (i.e., point 2 of the three key knowledge points, diffusion theory), the external atoms can move easily there. Due to the grain interface tending to reach a lower energy state (i.e., point 3 of the three key knowledge points, minimum-energy principle), the external atoms gathering at the grain interface to shrink the interatomic distance. When the interatomic distance is near $r_0$ locally, according to Fig. 2(b), the energy at the grain interface will be lowered. In other words, the fourth property of grain interface roots in the minimum-energy principle. Similarly, for the fifth property, the energy consumption is higher at the grain interface during the movement of dislocation, thus the dislocation is impeded. In contrast, the energy consumption is lower at grain interface during phase transformation, and the diffusion rate is higher there. Accordingly, the nucleation of new phase is preferred at grain interface, which corresponds to the sixth property of grain interface.

### 2.2.2 The Application of the Three Key Knowledge Points in Understanding Austenitization of Steels During Heating

For the heat treatment of steels, the process of austenitization is a primary step. The austenitization process is consist of four phases: (1) phase 1, austenite nucleation, (2) phase 2, growth of nuclei, (3) phase 3, dissolving of retained cementite, (4) phase 4, homogenizing of austenite.

The above four phases can also be understood basing on the three key knowledge points. For a clear and simple introduction, the eutectoid steel was chosen for presentation. In the eutectoid steel, the phase interface between ferrite and cementite presents a disorderly atomic arrangement and interatomic distance is higher than $r_0$. Thus, basing on point 1 of the three key knowledge points, the lower net force (see Fig. 2a) at the grain interface can contribute to the fast diffusion (i.e., point 2 of the three key knowledge points, diffusion theory) of atoms needed in austenite nucleation. Accordingly, the austenite nucleation (phase 1) prefers to occur at the phase interface between ferrite and cementite. In phase 2, the growth of nuclei is attribute to the fast diffusion (i.e., point 2 of the three key knowledge points, diffusion theory) and the trend of reaching a lower energy state (i.e., point 3 of the three key knowledge points, minimum-energy principle). When it comes to phase 3, since the more prominent difference in lattice structure between austenite and cementite than that between austenite and ferrite, the ferrite can be dissolved more quickly and a part of cementite is remained. In order to make the remained cementite dissolve completely, more time is need. Once the process comes to an end, it is easy to know that the carbon concentration at the site of the remained cementite is higher than that without the remained cementite. The variation in carbon concentration will fail the coming homogeneous plastic deformation. Though, this state can lead to a automatic diffusion due to the minimum-energy principle (i.e., point 3 of the three key knowledge points), its rate is not acceptable in engineering. Therefore, phase 4, homogenizing of austenite, at a high temperature is coming to reach a homogeneous element concentration and a lower energy state.

### 2.2.3 The Application of the Three Key Knowledge Points in Understanding the Recrystallization Temperature of Steels

Recrystallization is a key process for softening the deformation strengthened materials through the nucleation and growth of new grains. For steels, the recrystallization only initiates at a temperature above room temperature. The recrystallization temperature is influenced by three factors: (1) factor 1, degree of pre-deformation, (2) factor 2, purity of metals, (3) factor 3, heating rate and holding time. Usually, the recrystallization temperature decreases with the increase in degree of pre-deformation and heating holding time, and it is contrary for the purity of metals and heating rate.

For factor 1, it is known that a larger pre-deformation means more defects in the steel, and the steel presents a higher energy state. Due to the minimum-energy principle (i.e., point 3 of the three key knowledge points), the higher energy gradient will lead to an easier recrystallization and a lower recrystallization temperature. While, when it comes to factor 2, for a steel with a lower purity (i.e., a higher impurities), the impurities, such as the high melting temperature elements or particles, can impede the diffusion of atoms and the migration of grain boundaries (i.e., point 2 of the three key knowledge points, diffusion theory). Namely, the growth of new grains in recrystallization is inhibited. Thus, the recrystallization is elevated to a higher temperature in the low purity steels. For factor 3, a higher heating rate means a lower true equivalent-state temperature the steel can reach in a limited time, the diffusion rate (i.e., point 2 of the three key knowledge points, diffusion theory) can not reach to a high level swiftly, which results in a slow recrystallization or a high recrystallization temperature. While, a longer hold time can assist the diffusion and migration of grain boundaries, and the consequent recrystallization temperature is lower.

### 2.2.4 The Application of the Three Key Knowledge Points in Understanding the Surface Hardening

Surface hardening of materials is usually required under the condition of that the materials will serve under the loading of bending, impact, torsion, or friction. For materials imposed with these loads, the materials' surface should be in high strength, hardness, fatigue strength, and wear resistance, and the inner materials' matrix should possess proper ductility and toughness. In order to achieve a combination of these performances, surface hardening process, such as surface quenching, carburization, nitridation and etc. are applied in engineering. All of these surface hardening processes can be understood basing on the three key knowledge points.

For surface quenching, the technology of inductive heating is widely used to heat the materials' surface, and the surface hardening thickness is determined by frequency. As the frequency increases, the surface hardening thickness will decrease. This is because a higher frequency means a shorter period. It is assumed that the heating rate keeps the same. Thus, a shorter period will result in a high temperature surface zone with a smaller thickness, and the material in this zone is austenitized while the other zone is not austenitized. At a high temperature, more carbon atoms can dissolve into the austenitized zone (i.e., point 2 of the three key knowledge points, diffusion theory). After quenching, the diffusion rate of the atoms declines sharply, during the phase transformation from austenite to martensite, plenty of carbon atoms are locked in the martensite (i.e., point 2 of the three key knowledge points, diffusion theory). It is known that the hardness and strength of martensite are quite high and they increase with the increase in carbon content. Thus, the material with a small thickness surface hardening zone can be obtained. Since the inner material matrix is not heated to the austenitized zone, no phase transformation occurs, which remains in lower hardness and strength but higher ductility and toughness.

For the carburization and nitridation processes, the carbon atoms and nitrogen atoms diffuse into the surface of materials (i.e., point 2 of the three key knowledge points, diffusion theory). The massive carbon atoms and nitrogen atoms lead to the disruption of the original atomic arrangement, and the interatomic distance of the newly formed material surface is lower than $r_0$. Basing on point 1 of the three key knowledge points, more work should be applied to break the bond. Accordingly, the material surface performs in a higher hardness and strength. On the contrary, since the carbon atoms and nitrogen atoms can not diffusion into the inner zone of the material matrix, the hardness and strength there are still in a low level. Accordingly, the goal of surface hardening is achieved through carburization and nitridation consequently.

### 2.2.5 The Effect of Application of the Three Key Knowledge Points in Learning

These three key knowledge points of the whole knowledge system of the textbook can also be applied in the other parts of the textbook, which is especially true in understanding recovery and recrystallization as well as heat treatment in Mechanical Engineering Materials.

In order to have a knowledge on the effect of these three key knowledge points on understanding the knowledge of this curriculum, a survey was conducted after class. The survey results of four classes were shown in Fig. 3, in which no less than 95%, 84%, 75%, and 90% of the surveyed students in class 1 to class 4 respectively think that these three key knowledge points are helpful or very helpful in learning. Clearly, most of the students think that these three key knowledge points are helpful for their study, which suggests that the positive application of reductionism in this curriculum is possible.

Due the potential of helpfulness of these three key knowledge points in learning Mechanical Engineering Materials, a new textbook is planned to be complied with annotations basing on these three key knowledge points. Before this work, another survey was also conducted. The survey results were presented in Fig. 4, in which no less than 98%, 81%, 90%, and 87% of the surveyed students in class 1 to class 4 respectively think that these three key knowledge points are helpful or very helpful for a more easily understandable textbook. The above results in Fig. 3 and Fig. 4 are inspiring and enlightening, and more works and investigations will be conducted to apply reductionism in engineering education.

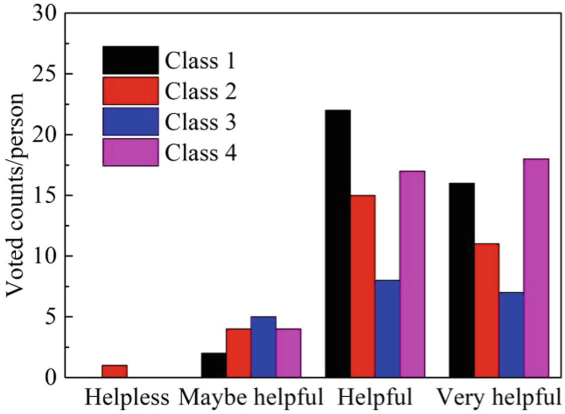


**Fig. 3.** Survey results of the effect of three key knowledge points on learning efficiency

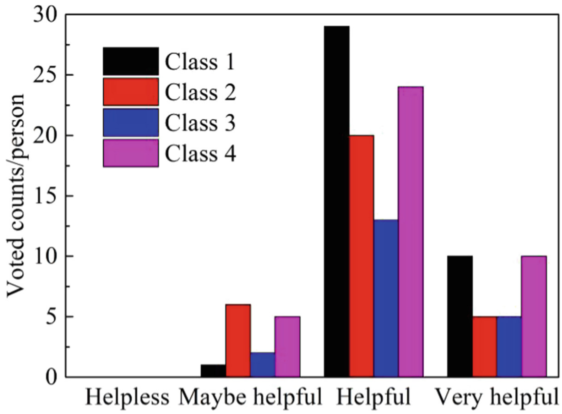


**Fig. 4.** Survey results of the helpfulness of three key knowledge points in newly complied textbook

## 3 Application of Holism

It is notable that the application of reductionism in understanding the knowledge in this curriculum is to utilize the method of breaking down a complex issue into basic or simple ones. While, the addition of these basic or simple issues probably does not equal to the original complex issue. In other words, the effect of reductionism is limited in analyzing some complex issues. While, holism is superior under this condition. However, compared with reductionism, the application of holism is less discussed in the teaching of engineering curriculum. In order to prove the effectiveness of holism in understanding the knowledge of Mechanical Engineering Materials, two examples were given as following.

### 3.1 The Application of Holism in Understanding the Influence of Electric Current Stressing on the Strength of Materials

There are several strengthening mechanisms in metals, including the strengthening by grain size reduction, solid-solution strengthening, strain hardening, dispersion strengthening, precipitation strengthening, and dislocation strengthening, etc. Most of these strengthening mechanisms can be understood basing on the inhibition of dislocation movement. While, there maybe a deviation in dislocation strengthening, which is especially true in the solder joints under electric current stressing.

For the solder under electric current stressing, the dislocation density increased due to the disruption of lattice structure induced by the collision of electrons. A higher dislocation density usually results in a higher strength. However, more Joule heat can be generated at a higher electric current density. The higher Joule heating induced temperature can result in the annihilation of dislocations, and thus lead to the reduction in strength. Clearly, there is an counteraction effect of dislocation generation induced by the collision of electrons and dislocation annihilation induced by Joule heating on the strength. Therefore, holism should be applied to analyze the consequence of this counteraction effect. In details, when the dislocation generation is the dominant factor at lower current density, the strength will increase compared with that without electric current stressing. On the contrary, when the dislocation annihilation is the dominant factor, the strength will decrease compared with that without electric current stressing. As a consequence, the strength of solder joints under current stressing at room temperature first increases and then increases with the increasing current density [9].

### 3.2 The Application of Holism in Understanding the Ductile-to-Brittle Transition of a Structure at Low Temperature

The ductile-to-brittle transition (DBT) usually occurs in materials at low temperature. In details, when the temperature keep decreasing, materials generally lose the ductility and become brittle. Once the material is in a brittle state, the structure constructed by the material may collapse suddenly and results in a disaster. However, the ductile-to-brittle transition temperature (DBTT) of a structure is not only affected by the intrinsic property of the materials, but also is influenced by the configuration and loading condition.

Similar with many other materials, the Sn3.0Ag0.5Cu solder shows a prominent DBT as the temperature declines. Besides the influence of temperature, for the line-type Cu/Sn3.0Ag0.5Cu/Cu solder joints under tensile stress, the DBT can also happen when the joint thickness decreases, and the DBTT increases with decreasing joint thickness [3]. While, for the ball grid array structure Cu/Sn3.0Ag0.5Cu/Cu solder joints under shear stress, the DBTT decreases with decreasing joint thickness, which is contrary to that in the former case [4]. Clearly, the variation of DBTT of a structure should not only be understood basing on a single factor (which is in a cognitive mode of reductionism), and the holism can be used to understand this issue clearly.

## 4 Conclusions

The preliminary application of reductionism and holism was conducted in teaching Mechanical Engineering Materials. The cognitive mode of reductionism is helpful for student to understand the knowledge system of this curriculum. While, the deficiency of reductionism in analyzing complex issues is prominent, and holism is superior at this condition. Moreover, the concurrent application of reductionism and holism can be in a higher efficiency for teaching.

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