

# Clad Metals: Fabrication, Properties, and Applications

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## 1. Introduction and Scope

Studying clad metals has been an active field of research in the last few decades. Clad metals are layered composites of two or more dissimilar metals [1]. These materials have remarkable potential to combine the desirable properties and/or characteristics of individual metals and alloys into composites that provide improved characteristics over the individual metals. In many cases, studies have been conducted from the viewpoint of the functional characteristics of clad metals. However, research on clad metals is actively underway that considers pricing and industrial competitiveness [2]. Because of their many advantages over single metals, clad metals are widely used in home appliances, cookware, and heat exchangers, as well as in energy storage, automotive, transportation, and electrical distribution applications [3]. Significant advances in clad metals have been achieved as a result of interdisciplinary research in related fields of metallurgical, mechanical, and electrical methods.

This Special Issue on “Clad Metals: Fabrication, Properties, and Applications” intends to collect the latest developments, written by well-known researchers who have contributed significantly to the research fields of fabrication, characterization, and applications of clad metals. The topics addressed in this Special Issue may include but are not limited to the following: bonding methods and principles, interface properties, metallurgical characterization, applications, and advantages of clad metals.

This issue examines the importance and manufacturing principles of clad metals. Their importance is examined in terms of their combined functionality and cost. Clad metal manufacturing principles are studied from theoretical and practical viewpoints in the atomic scale range. Roll bonding is currently the most widely used manufacturing method in industry and is therefore described in some detail below. Finally, I would like to add analysis and comments on nine excellent contributed papers in this Special Issue.

## 2. Clad Metals and Contributions

### 2.1. Importance of Clad Metals

In modern industries, functional materials with complex properties are required. As a result of efforts to satisfy these demands, various alloys and composites have been developed. Generally, clad metals are layered composites, which also include thick coatings on wire-shaped base materials.

Figure 1 shows two important applications of clad metals, with a schematic of electric cookware in Figure 1a. The material characteristics required for electric cookware are as follows: high thermal conductivity, high corrosion resistance, high scratch resistance, and light weight. However, it is difficult to satisfy these various requirements with a single material. For example, stainless steel has excellent corrosion resistance and scratch resistance, but is undesirable due to its low thermal conductivity and high density. In contrast, aluminum (Al) has satisfactorily high thermal conductivity and low density, but problematic low scratch resistance. Therefore, in order to obtain the various properties required by electric cookware, a three-ply [stainless steel/aluminum/stainless steel] sandwich structure is often used.



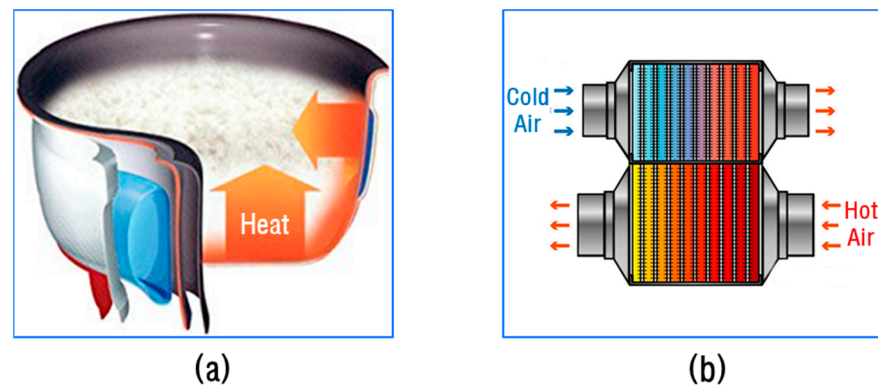
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**Figure 1.** Clad metal application examples: (a) container in electric cookware, (b) heat exchanger.

Another important application of clad metals is its use in heat exchangers. The heat exchanger is defined as a device that efficiently transfers heat from a high-temperature liquid or gas to one at a low-temperature. Figure 1b shows a conceptual diagram of the structure and principle of a heat exchanger. In this case, the heat exchanger material should have excellent formability, high corrosion resistance, and high thermal conductivity. Titanium (Ti) has excellent corrosion resistance but forming is difficult and expensive. Stainless steel is inexpensive and has excellent corrosion resistance and formability but low thermal conductivity. Aluminum (Al) and copper (Cu) have lower corrosion resistance but excellent thermal conductivity and formability. Therefore, if clad metals could be manufactured using some combination of these materials, competitiveness in terms of function and cost could be improved.

## 2.2. Manufacture of Clad Metal

Generally, clad metals are manufactured using processes that begin with the different metals being in close contact with each other. Cladding is different from welding and gluing in that it bonds without using an adhesive and has a low-temperature process below the melting point of any of the materials. Roll bonding, explosive bonding, brazing, and extrusion bonding are the main processes used to manufacture clad metals [1]. The roll bonding manufacturing method is described in detail below.

Roll bonding is a process that can continuously manufacture clad metals; therefore it has a low cost and is currently widely used in industry. Figure 2 shows an example of the roll-bonding process. Three different metal sheets (copper, stainless steel, and copper) are used to fabricate three-layer clad metal products. In this process, bonding occurs only when the surfaces are properly cleaned through pre-treatment and then compressed with a sufficiently large pressure between a pair of rolls. The pressure must be enough to deform the metal and reduce its thickness. In some cases, additional heat must be supplied, especially when the metal does not have sufficient ductility.

Figure 3 shows a conceptual diagram of the bonding principle between two metal plates during the cladding processes. In the figure, the  $x$ -axis represents the distance between the two metal plates in terms of interatomic distance. The  $y$ -axis represents the magnitude of the bonding force as a function of this inter-plate distance. In the figure, the upper part of the  $y$ -axis represents an attractive force, which is the driving force for cladding. The magnitude of the attractive bonding force is weak when there is a large distance between atoms across the plate-to-plate interface. However, when the spacing between the facing atoms is reduced, the magnitude of the attractive force increases, reaching a maximum at a specific spacing. If the distance between the facing atoms is further reduced, the magnitude of the attractive force reaches zero ( $F = 0$ ), which becomes the distance between the atoms at equilibrium. By applying greater pressure and reducing the spacing between the atoms, the repulsive forces become dominant and the facing atoms repel each other.

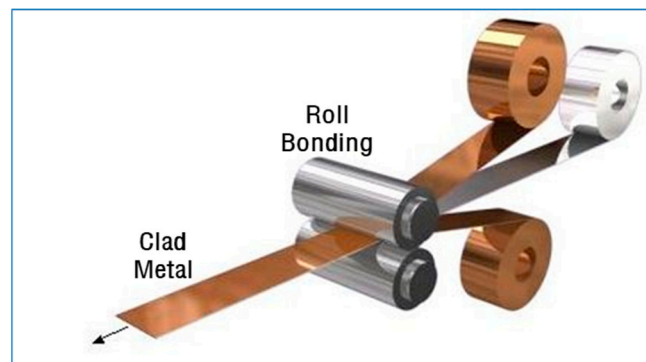


Figure 2. Schematic illustration of the roll bonding process for manufacturing three-ply clad metals [4].

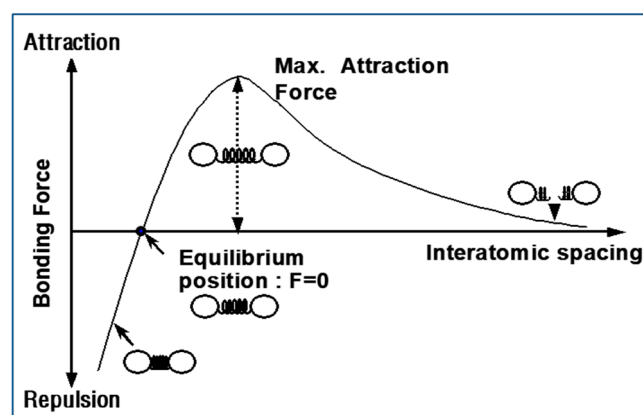


Figure 3. Schematic illustration of the bonding force dependence on spacing between atoms in the facing plates; based on [5].

The average distance between facing atoms in the clad metal bonding state is the distance at which the attractive force becomes zero, which is the point at which the attractive and repulsive forces are equal. In addition, the critical applied pressure during cladding must be high enough such that the value of the attractive force approaches the maximum value. It is known that the spacing between facing atoms where the attractive force is at a maximum is only a few atomic distances. Therefore, in order to reach this close spacing, it is essential that the pressure be sufficient to reduce the surface roughness through plastic deformation, as well as to produce breakage of the oxide layer on the surface of the base material [4].

In particular, Figure 3 might be relevant for the rolling of pure gold, but most metals have an oxide whose irregular morphology will mechanically prevent contact between the metals to be bonded. In addition, the oxide-to-oxide contact is not likely to provide significant useful bonding because of its irregular surface and high hardness. The oxides need to be fractured by tensile forces during the extension of the metals by the roll forming process. The freshly revealed metals can then start to deform together initiating bonding as Figure 3 suggests. However, it seems probable that the patches of oxide-to-oxide regions of the interface will be a permanent feature, inhibiting any significant bonding. Thus the overall bonding of the two metals will only improve steadily with increasing deformation, particularly increasing extension of their area, but perhaps never reach 100 percent.

### 2.3. Contributions

In this Special Issue, nine original research papers are published. In terms of the clad metal manufacturing method, three papers can be grouped into roll bonding processes [6–8], two are casting processes [9,10], two concern spray coatings [11,12], and the final two are unique [13,14]. A closer look at the characteristics and importance of each paper follows:

In the first group, clad metals were fabricated by a roll bonding process. Giudice et al. [6] describe their work on the “Metallurgical Characterization of the Interfaces in Steel Plates Clad with Austenitic Steel or High Ni Alloys by Hot Rolling”. In this study, simulations based on theoretical diffusion modeling were integrated into the experimental characterization by introducing a cladding parameter that acts on the diffusion bonding efficiency. Wang et al. [7] present work titled “Investigation on Springback Behavior of Cu/Ni Clad Foils during Flexible Die Micro V-Bending Process”. This paper describes work on the flexible die micro-V-bending behavior of Cu/Ni foils. The results show that the springback angle increases with an increase in the bending angle and annealing temperature. Kim et al. [8] contribute a paper titled “Effects of Intermetallic Compound Layer on Peel Strength and Crack Propagation Behavior in Cu/Al/Cu Clad Composites”. In this study, the effects of interfacial modification in tri-layered Cu/Al/Cu composites by heat treatment on the interface stability and crack propagation were investigated.

The second group of papers covers casting processes. Münster et al. [9] offer a paper titled “Copper Clad Steel Strips Produced by a Modified Twin-Roll Casting process”, in which the bonding strength and formability of clad strips were qualitatively examined in rolling and bending tests. Lee et al. [10] present a paper titled “Change of Microstructure and Hardness of Duo-Casted Al3003/Al4004 Clad Material during Extrusion Process”. The specimen of duo-cast Al3003/Al4004 clad materials was circular in cross section; it was composed of Al3003 (outside) and Al4004 (inside) materials.

In the third group, the cladding metal was fabricated by spray coating. Park et al. [11] describe their work on the “Influence of Laser-Assisted Fusing on Microstructural Evolution and Tribological Properties of NiWCrSiB Coating”. The aim of this study was to examine the applicability of a diode laser-assisted fusing treatment and a temperature-control system to a NiWCrSiB thermal spray coating to enhance the wear resistance of continuous-casting molds. As a result, laser-assisted fusing treatment enhanced the tribological performance of the thermal-sprayed coating. Kim et al. [12] present work titled “Effect of Heat Treatment Condition on Microstructural and Mechanical Anisotropies of Selective Laser Melted Maraging 18Ni-300 Steel”. In this study, maraging steels were fabricated by a selective laser melting process, which is a type of layer additive manufacturing process (3D printing), and their microstructures and mechanical properties were investigated in terms of post-heat treatment conditions.

There were two papers in the fourth group. Lee et al. [13] describe their work on the “Development of Equivalent Beam Model of High Burnup Spent Nuclear Fuel Rods under Lateral Impact Loading”, in which the effect of cladding between the fuel pellets and cladding tube wall in a reactor environment was investigated using finite element analysis. Finally, Shin et al. [14] contribute a paper titled “High Temperature Mechanical Properties and Wear Performance of B<sub>4</sub>C/Al7075 Metal Matrix Composites”. In this study, high-volume-fraction B<sub>4</sub>C reinforced Al matrix composites were fabricated using a liquid-pressing process. The composites produced by the liquid-pressing process showed superior wear resistance compared to the Al matrix.

### 3. Conclusions and Outlook

The contributions highlighted in this Special Issue indicate that clad metals are still a widely studied topic from a scientific viewpoint and in industrial practice. Notably, the newer clad metal manufacturing methods differ from conventional roll bonding. Clad metals originally referred to layered composites manufactured by physically bonding two different metal plates using high pressure or high heat. However, as indicated herein, a recent trend is the increasing research on reducing the manufacturing cost of clad metals by adding liquid metal to the base material using the casting method. In addition, methods for manufacturing clad metals by thick spray coatings are also increasing. Recently, clad metals have been manufactured by applying hundreds of thin layers via the 3D printing process; spreading metal powder to the base material followed by melting using a high-powered laser beam. The primary reason for these studies on clad metal manufacturing is to obtain

the desired combination of physical properties with reduced costs. Hence, this Special Issue will be useful for students and researchers in both academia and industry.

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