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FRACTAL ARCHITECTURE PRINCIPLES IN SOLID-STATE ALLOYING WITH KIRIGAMI STRUCTURES

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Abstract

This report presents an innovative approach to solid state alloying using a kirigami inlay to produce functional gradient materials (FGMs). This deformable inlay, which dissolves into the matrix according to the principles of fractal architecture, allows the distribution of alloying elements in the matrix to be controlled during roll-bonding and subsequent heat treatment. The resulting structures exhibit self-similarity due to the geometry of the inlay, which is scalable at different levels. This paves the way to materials with new functional properties.

Keywords: solid-state alloying, functionally graded materials, kirigami inlay, fractal architecture, roll bonding

Innovative approaches to create materials with superior properties are required for the rapid advancement of materials science and engineering. This drives to explore and develop the principles of fractal architecture in solid-state alloying processes to create Functionally Graded Materials (FGMs). FGMs are generally considered to be advanced composite materials characterized by a gradual variation in composition and structure that enhances their performance in targeted applications. The hallmark of the approach, presented here, is the use of kirigami, the ancient Far Eastern art of cutting sheet materials to distribute alloying elements within the matrix during pressure bonding. In simplified terms, such a process can be thought of as the hot roll bonding of at least two half-matrices of sheet with expanded mesh [1] between them. In such a process (Figure 1a), the kirigami inlay (1) is placed between sheet matrices (2) and rolled in rolls (3) under certain thermal-deformation conditions until the two halves of the matrices are completely bonded, surrounding the deformed inlay [2].

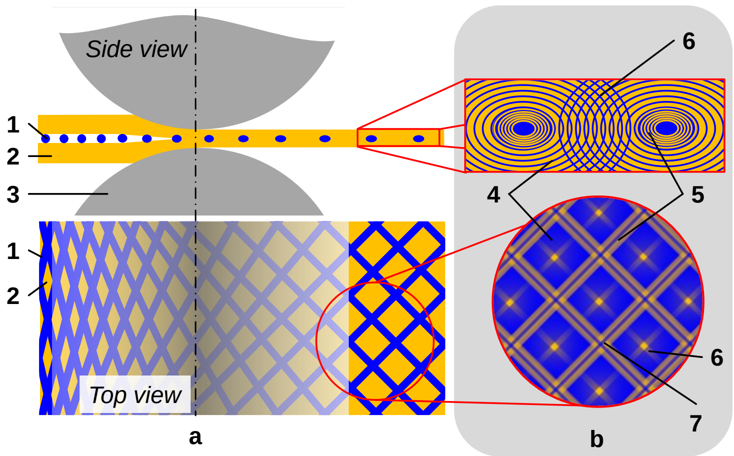

Figure 1. The schematic visualization of solid-state alloying using roll bonding with subsequent heat treatment; a – transformation of the inlay during the roll bonding; b – mutual diffusion of the matrix and the inlay. 1 – kirigami inlay; 2 – matrix material; 3 – roll; 4 – isophase (isotonic) lines, illustrating the diffusion of the alloying inlay in the matrix (A→M); 5 – isophase (isotonic) lines, illustrating the diffusion of the matrix material in the alloying inlay (M→A); 6 – area of intersections of 4, which can be described with principles fractal geometry. 7 – area of intersections of 5, which can be described with principles fractal geometry.

The resulting composite is then thermally treated to achieve the desired phase content and distribution. Figure 1b schematically illustrates the diffusion of the mesh inlay into the matrix (4) and the matrix material into the inlay (5) during the subsequent heat treatment. This architects the fractal diffusion patterns of isophase (isotonic) cross-points (6 and 7) in the Mandelbrot set [3], [4] of the ellipsoid surfaces, which is called to provide geometric rigidity of potentially brittle phases. The kirigami-inspired deformed inlay, in this case, appears as a solid alloy structure. Such an approach uses patterns of the alloy structure to manipulate and control diffusion and precipitation at the microscale, with subsequent scaling down to the nanoscale and up to the macroscale. This means that the final content and distribution of the alloying element within the matrix is strictly predetermined by the shape and size of the basic element of solid alloying structure, which in this case, plays the role of the fractone. This term describes a fractal's basic building block, from which self-similarity and recursion build its structure. It was implemented by F. Mercier, a neurologist, who wrote in his work [5] that fractones capture growth factors from the brain ventricles, then bind and send these molecules to the neurogenic zone or adjacent neural structures. Thus, the solid-state alloying can be represented as the evolution of the composite material with kirigami inspired 3D shape of inlay obtained with plastic deformation into a sequence of intermetallic phases as well as solid solutions. The shape of the space occupied by the current phase with current concentration at the macroscale is similar to the initial shape of the inlay, and the dimensions are scaled in a fractal recursive manner. Distribution and stoichiometry of these phases depend on the diffusion potential, location of the inlay within the matrix, as well as the density and character of microstructural defects. This evolution is driven by a heat treatment whose time-temperature line must navigate to the required phase content as well as the dimensions of the 3D figures built of family of isophase as well as isotonic surfaces. 3D crossings of such surfaces (Figure 1b) architect recursing patterns according to fractal geometry. In this way, the resulting structure is architected as a fractal volumetric network composed of both isophase and isotonic lines of solid solutions and intermetallic phases, which has the potential to lead to novel material properties and functionalities [6]. Complex polynomial equations of the Mandelbrot set can be used to describe the set of shapes of isophase (isotonic) points formed during solid state diffusion of the 3D structure of the alloying element in the matrix. Such hypothesis is based on the approach presented in the fundamental work [3], where the possibility of such scenario is predicted both mathematically and thermodynamically. More recent work [4] describes how the shape of the internal alloy structure inspires the fractal recursion. The legacy of many years of research on the effect of severe plastic deformation [7] provides us with the effect of turbulence of shear flow in some areas of roll bonding of wire-reinforced aluminum composites [8]. Modern development of computational methods as well as the capability of available computational resources allow to summarize these mathematical and engineering phenomena.

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Використання приц背ципів фрактальної архітектури у твердотільному легуванні кірігамі структурами

Анотація

У доповіді представлено інноваційний підхід до твердотільного легування з використанням пласкої кірігамі-вставки для створення функціональних матеріалів (FGM). Пластично деформована вставка, яка розчиняється в матриці у відповідності до принципів фрактальної архітектури, дозволяє керувати розподілом легуючих елементів у матриці під час прокатки-з’єднання та подальшої термообробки. Отримані структури демонструють самоподібність, зумовлену геометрією вставки, що масштабуються на різних рівнях. Це відкриває шлях до матеріалів з новими функціональними властивостями.

Ключові слова: твердотільне легування, функціональні матеріали, кіригамі-вставка, фрактальна архітектура, прокатка-з'єднання

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