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KIRIGAMI INSPIRED SOLID-STATE ALLOYING (KISA) METHOD OF CREATION OF FUNCTIONALLY GRADED MATERIALS

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Abstract. *Kirigami-inspired solid-state alloying (KISA) is an innovative technique that applies kirigami principles to control the distribution of alloying elements within a matrix during pressure bonding. By employing precise cuts and patterns, KISA manipulates diffusion and precipitate formation at micro- and nanoscale levels, leading to tailored material properties. This method eliminates challenges associated with conventional liquid alloying, such as oxidation and element loss, while enabling controlled microstructure evolution through roll bonding and heat treatment. Key advantages include improved phase distribution, enhanced interfacial properties, and adaptability for various material types, including powders and amorphous substances. KISA presents new opportunities for designing functionally graded materials with customized mechanical, electrical, and thermal characteristics.*

Keywords: *kirigami, matrix, deformation, bonding, functionally graded material*

Kirigami-inspired solid state alloying is an innovative technique that uses the principles of kirigami, the Far Eastern art of cutting, to distribute the alloying element within the matrix during pressure bonding. This approach uses precise cuts and patterns to manipulate and control diffusion and precipitate formation at the micro- or nanoscale, potentially leading to novel material properties and functionalities. This means that the final content and distribution of the alloying element within the matrix is determined by the shape and size of the solid inlay. These properties, in turn, are influenced by the initial shape of the cuts and the subsequent transformation of the cut inlay during the pressure bonding of the matrix parts. Figure 1 shows an example of the transformation of the initial kirigami structure (rhombic mesh) into the inlay with square cell shape during roll bonding and illustrates diffusion of the inlay during subsequent heat treatment. In such a process, the kirigami structure is placed between sheet matrices and rolled under certain thermal-deformation conditions until the two halves of the matrices are completely bonded, surrounding the deformed inlay. The resulting composite is then subjected to a thermal treatment to obtain the required phase content and distribution.

It is clearly visible from Figure 1 that all geometric parameters of the input components are subject to change in the deformation zone in parallel with the bonding of the matrix material. This method of roll bonding was initially invented as a way of obtaining composite materials [1, 2] with improved mechanical and fire resistance properties. The nature of these improvements depends on the strain-stress state in the deformation zone, which also has a hardening effect on the inlay material.

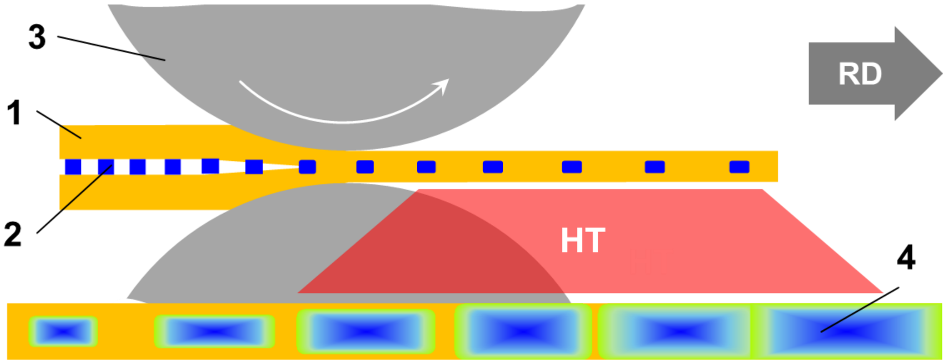

Figure 1 – Schema of the inlay transformation during roll bonding: 1- matrix material;
2 – deformable inlay; 3 – upper roll;
4 – visualization of diffusion of the inlay material into the matrix material;
RD – rolling direction; HT – heat treatment

Thus, the solid state alloying of such a structure can be represented as the evolution of the composite material into a sequence of intermetallic phases as well as solid solutions, the distribution and stoichiometry of which depend on the location of the inlay within the matrix, as well as the density and character of microstructural defects inspired by plastic deformation. This evolution provided with a heat treatment, the time-temperature line of which must navigate to required phase content.

With regard to such features of roll bonding, it is appropriate to highlight the key advantages of solid state alloying as compared to conventional alloying:

- Solid-state alloying avoid the problems associated with high-temperature processing, such as vaporization or decomposition of lower-melting elements, when the components have significantly different melting points.
- The risk of oxidation and contamination that can occur in molten metal at high temperatures can be eliminated with this method.
- In the case of high entropy alloys, where maintaining uniformity in a liquid state can be a challenge, the solid state technique can provide a controlled architecture of alloying elements both in planes and in volume.

- KISA, due to controlled strain-stress conditions during the roll-bonding as well as due flexible timing during the heat treatment, provides precise control over the microstructure, including the stoichiometry and distribution of intermetallic phases.
- Continuous juvenilization of the surface layers of the components in a low-oxidation atmosphere during roll bonding forms the complex interface, which has an effect on the kinetics of intermetallic phase formation.

This method can be used to develop materials with tailored mechanical, electrical and thermal properties. Potential applications include adaptive materials, especially biodegradable materials, and novel structural components that require specific performance characteristics that cannot be achieved by traditional alloying methods. The alloying inlay can be a polycrystalline body, or a powder, or an amorphous substation dispersed in a prepatterned matrix. The use of the powder inlay requires prior patterning of the matrix and careful filling of the pattern before the roll bonding [3]. In this way, a controlled and precise distribution of the alloying powder in the interfacial plane can be achieved. Another promising aspect is the dynamical contact interaction between the alloy particles and the juvenile layers of the matrix material during the subsequent roll bonding [4]. Overall, the kirigami-inspired solid-state alloying represents a fusion of traditional art techniques with materials engineering, opening up new opportunities for synergistic effects in the design and fabrication of functionally graded materials.

Key tools of the KISA

As we can see, the KISA can be imagined as the sequence of the technological elements of roll bonding and heat treatment, namely the rolling reduction, the rate of deformation, the friction, the roll diameter and, last but not least, the temperature during the whole process. The content of these elements controlled via following tools:

1. **Material Combination.** This tool is used to define the combination of matrix and inlay materials to achieve the required set of properties. These properties are divided into three groups:
   a. Electrical and magnetic;
   b. Mechanical and structural;
   c. Corrosion and degradation.

   This tool is characterised by two limiting factors:
   - the rheological behaviour of the material pair during common plastic deformation. Here it is necessary that these materials have sufficient ductility in the selected temperature range;

- kinematics of mutual diffusion in the solid state with formation of intermetallic phases. The important parameters are the diffusion rates and directions.

2. **Character of surface interaction**. This tool is useful for understanding which interfacial effects are expected, for example, joinability, sensibility to the interaction with atmosphere, roughness, etc.

3. **Geometrical parameters of the components**. The shape of the kirigami pattern and the thickness of the layers determine the interaction of the components during roll bonding and subsequent heat treatment. This forms the basis for the further content and distribution of phases within the new material. Optimal geometric parameters of the components must be designed iteratively, taking into account the geometry of the deformation zone, including its elastic part.

4. **Evolution of the components geometry and properties during roll bonding**. The roll bonding of KIC is characterized by extreme inhomogeneity. Flow curves and thermokinetic diagrams are not always sufficient to predict the technological ductility of materials used as components of KISA.

5. **Evolution of the deformed components during heat treatment.** This tool is a continuation of tool 1 as follows: the kinetics of diffusion and formation of intermetallic phases is the objective of the KISA procedures. The characteristic of KISA in this sense is the enhanced role of microstructural defects generated by inhomogeneous plastic deformation as a driving force of the thermodynamic process.

Conclusions

1. Kirigami inspired solid-state alloying (KISA) is an innovative method for creating functionally graded materials based on an art-meets-science approach.

2. KISA brings new features to the solid state alloying process: controlled volumetric distribution of alloying components and deformation-inspired microstructural defects that affect the distribution and stoichiometry of intermetallic phases and solid solutions.

3. KISA allows the use of not only solid inlays, but also powder and amorphous substations as alloying elements.

4. Five key tools that determine the content of the technological elements during KISA are the subject of further study.

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ТВЕРДОТІЛЬНЕ ЛЕГУВАННЯ НА ОСНОВІ КІРІГАМІ-СТРУКТУР (ТЛКС) ДЛЯ СТВОРЕННЯ ФУНКЦІОНАЛЬНИХ МАТЕРІАЛІВ

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Анотація. *Твердотільне легування матеріалів на основі кірігамі-сруктур (ТЛКС) – це інноваційна технологія, яка застосовує принципи кірігамі для контролю розподілу легуючих елементів у матриці під час з'єднання тиском. Використовуючи точні розрізи та шаблони, ТЛКС керує дифузією та утворенням інтерметалідних фаз на мікро- та нанорівнях, що призводить до формування функціональних властивостей матеріалу. Цей метод усуває проблеми, пов'язані зі звичайним рідинним легуванням, такі як окислення і втрата елементів, одночасно забезпечуючи контрольовану еволюцію мікроструктури під час прокатки-з'єднання і подальшої термічної обробки. Основні переваги включають покращені розподіл фаз заданої стохіометрії, міжфазні властивості та адаптивність до різних типів матеріалів, включаючи порошки та аморфні речовини. ТЛКС відкриває нові можливості для розробки функціональних матеріалів з програмованими механічними, електричними та тепловими характеристиками.*

Ключові слова: *кірігамі, матриця, деформація, з'єднання, функціональний матеріал*