Opportunities and challenges of additive manufacturing toward magnetic refrigeration

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Characterized by high efficiency and environmental sustainability, magnetic refrigeration represents a compelling avenue for cooling technology innovation and makes it a viable candidate for displacing conventional vapor-compression refrigeration. Magnetic refrigeration is grounded in the magnetocaloric effect whereby temperature changes in a material result from the imposition or removal of an external magnetic field. Noteworthy progress has been achieved, with a larger number of magnetic refrigeration prototypes working at different temperature regimes having been developed, and considerable research and development efforts are still underway.

Within the domain of magnetic refrigeration, active magnetic regenerators emerge as a focal point, which can be categorized into rotating designs and reciprocating designs. Notably, the rotary prototypes demonstrate superior refrigeration efficiency compared to their reciprocating counterparts. Prominent materials employed in such refrigeration systems include Gd-based alloys or other first-order phase transition materials such as La-Fe-Si and Mn-Fe-P-Ge. Till now, the systems are designed by the Astronautics Technology Center (USA) attaining 3024 W cooling power at zero temperature span and Toshiba Corporation achieving 42 K temperature span under no load condition, underscoring the efficacy of this technology.

Moreover, magnetic refrigeration finds potential application in nitrogen and hydrogen liquefaction, exhibiting higher thermal efficiency and entropy density relative to conventional liquefaction techniques involving Joule-Thomson valve. These room/low-temperature prototypes employ either packed particle beds or stacked plane plates separated by spacers to provide channels for heat exchange fluid. However, a significant limitation arises as the particle beds are susceptible to segregation and sedimentation, leading to a consequential pressure drop along the length of the regenerator. The parallel plate beds with high heat transfer efficiencies, whose thickness is around 0.10 - 0.15 mm and spacing around 0.05 - 0.075 mm, pose challenges in their preparation by conventional machining methods. The implementation of stacked plane plates with unsatisfactory geometric dimensions increases the heat transfer time between the regenerator and the exchange fluid, leading to a low operating frequency of the prototypes.

In the pursuit of reducing the transfer time and enhancing the cooling effi-
ciency, an attractive solution involves the preparation of a microchannel structure with a high specific surface area and suitable pressure drop of liquid flows. Such structures may include configurations such as serpentine channels, hollow droplet channels, triply periodic minimal surface porous structures, and topology-optimized layout channels. However, the preparation of products featuring internal fluid channels by conventional formative or subtractive manufacturing proves to be intricate. Particularly, the successful manufacture of certain products becomes prohibitive when internal channels exhibit high complexity or diminutive sizes.

Additive manufacturing (AM) emerges as an innovative solution for the preparation of microchannels as shown in Figure 1, leveraging its capacity to digitally construct three-dimensional objects layer by layer. Kitanovski 1 has pointed out that AM would eventually represent the basis for the mass production of magnetic refrigerants. Also known as 3D printing, AM affords a unique advantage in optimizing geometries for enhanced thermal efficiency, concurrently reducing lead time and material wastage. AM not only demonstrates great advantages in the preparation of microchannels but also provides a new way to improve the properties of materials such as adjusting the phase transition temperature to widen the temperature range, refining grain to reduce hysteresis, obtaining a higher volume percentage of functional phase after a short-time annealing. Several magnetocaloric materials, including La–Fe–Si, Mn–Fe–P–Si, La–Ca–Mn–O, Al–Fe–B, and Ni–Mn–Sn-based alloys, have been successfully prepared by laser powder bed fusion, 3D ink-printing, binder jetting or directed energy deposition. The attention has been paid to the channel design, process parameters, microstructural development, defects, and magnetocaloric effects in AM. By optimizing process parameters, the values of the magnetocaloric effects have been close to those of alloys prepared by conventional manufacturing. The defects mitigation and homogeneous grain structure/composition are obtained during subsequent annealing. Notably, the AM La(Fe, Co, Si)13 geometries have exhibited remarkable durability, surviving more than 10⁴ cycles in the presence of a magnetic field without heat transfer fluid.

Although AM technologies can bring many advantages for channel design and manufacture, certain challenges (e.g., powders, AM process, properties of AM parts, shape design, heat transfer optimization) persist. The spherical powders are usually preferred for their better flowability, layer spreading, and powder packing. Whereas, magnetocaloric materials often contain volatile and oxidizable elements, resulting in high-quality powders that are not easy to prepare. The AM process and post-fabrication treatments are also crucial for quality assurance. In-situ monitoring of these processes can detect potential defect formation and control the process parameters in situ. Thus far, it is not easy to accurately detect and identify defects by in-situ monitoring, because of difficult assessments of image distortion, background radiation and material emissivity. Moreover, imperfections such as microstructure inhomogeneity, non-functional phase formation, pores, cracks, powder adhesion, poor channel quality, and contour accuracy are prone to occur in the AM parts. These imperfections will degrade the magnetocaloric effect, mechanical properties, flow efficiency, and heat transfer efficiency of the fluid. Additionally, the systematic study of heat transfer efficiency between the AM microchannel parts and fluids is lacking in magnetic refrigeration, prompting the need for scientific design criteria encompassing overall arrangements and local shapes of fluid channels to meet the requirements of the refrigeration prototype. Therefore, urgent attention needs to be paid to address the gaps.

The critical factors that affect the performance of AM products are raw materials, processing conditions, and post-processing. The stable and mature processing technique needs systematic researches to obtain starting powders with high sphericity, low oxygen content, and precise composition. During 3D printing and post-fabrication treatments, in-situ monitoring of defect and feedback control methods is expected to experience a substantial step forward with the development of computationally efficient methodologies. For the design of channel geometries, a particularly creative avenue involves coupling AM techniques with numerical models of thermal fluid behavior in prototypes, which is of high potential to produce novel, compact, high-performance heat exchanger for magnetic refrigeration. Essential to this endeavor is the establishment of high-throughput data sources that integrate optimal channel designs, powder characteristics, AM process, post-heat treatments and sample quality, with the ultimate goal of achieving minimal defects, minimum waste, precise channel quality control, and desirable microstructure properties relationships.

Despite the scientific and technological challenges are inherent in AM technology, it remains a promising way for the fabrication of microchannel structures with high specific surface areas and enhanced performance of refrigeration prototypes. At present, relevant research for AM magnetocaloric materials is in its nascent stage, signifying that further investigations are urgent to advance the practical application of magnetic refrigeration in diverse scenarios. Future endeavors in this realm hold potential applications in small household appliances, medical refrigeration, gas liquefaction, detectors, and other fields. Therefore, AM represents a transformative force in realizing the broader applicability and efficacy of magnetic refrigeration technologies.

REFERENCES

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DECLARATION OF INTERESTS
The authors declare no competing interests.