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Mechanical Metamaterials for Enhancing Downhole Survivability

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ABSTRACT

Accessing the true potential of geothermal energy requires developing downhole technology that can survive the punishing environmental conditions of Enhanced Geothermal Systems (EGS). Legacy materials and methods lack the operational capabilities to perform at the high temperatures, high pressures, and corrosive chemistries in EGS wells. This paper discusses the burgeoning field of mechanical metamaterials and their specific applications to downhole technology. Mechanical metamaterials use geometrically patterned units to manipulate the physical properties of an existing material, often with the result of achieving characteristics that are not possible in conventional materials. Mechanical metamaterials can be designed that cloak sound, mitigate vibrations, are stiff under pressure but soft under shear, and have large auxetic expansion. This paper will highlight several applications of particular interest for downhole equipment, showcasing how programmable thermal expansion and compliant expansion can be incorporated into modern tools. Additionally, manufacturability of metamaterials at the quantity and quality required to meet industry needs will be discussed briefly.

1. Introduction

Traditional geothermal energy contributed 1.8% to the 2019 domestic renewable energy supply, or about 0.2% to the total US energy budget. Increasing contributions from geothermal energy requires access to higher temperatures, which generally means great drilling depths. Over the last few decades Enhanced Geothermal Systems (EGS) has emerged as the concept for how modern deep wells may function. Unfortunately, the massive costs for drilling equipment and the likelihood of material failure contribute to the chances that a deep EGS well project will be abandoned.

To respond to the problem of equipment failure, technology development must focus on improving downhole survivability. The challenges associated with the EGS environment include (1) long-term exposure to temperatures above 200 Celsius, (2) the presence of corrosive fluid chemistries and (3) pressures above 150 MPa. Even ubiquitous elements of a drilling program such as the casing and simple elastomeric sealing elements suffer from these conditions, and the legacy materials inherited from oil and gas high temperature wells are not sufficient to meet these challenges.

In this paper we discuss the nascent field of “mechanical metamaterials”, a class of geometrically designed cellular materials that can be incorporated into existing downhole tools or used to design modern multi-functional parts. Metamaterials function similarly to composites, in that they can replace bulk metals and plastics with high strength, low weight alternatives for some applications. Metamaterials are primarily material agnostic, however, so they offer a unique perspective into engineering high temperature components or improving on old designs. We first give a brief introduction to the field of mechanical metamaterials in general, and review how ordered hierarchy and structure in conventional materials can lead to exotic or extreme properties. Following this we briefly address manufacturability of mechanical metamaterials and compare the relative benefits and disadvantages for using complex geometries with advanced manufacturing. Finally, we highlight two use cases for EGS wells, where mechanical metamaterial engineering and ideas can be used in tandem with conventional material selection to design flexible casing connectors and replace elastomeric sealing elements.

2. Overview of mechanical metamaterials

While mechanical metamaterials have been discussed in the academic context for more than 30 years (see e.g. Lakes 1987, Gibson and Ashby 1999, Shang and Lakes 2007) industrial application has remained limited. In part this is due to the geometric complexity that many mechanical metamaterials require to perform their function, and thus are difficult to manufacture, but often the lack of adoption arises from the inability to find an appropriate use-case.

Mechanical metamaterials, occasionally referred to as architected solids or cellular materials, have a layer of hierarchy or geometric structure on top of their atomic or molecular composition (Fig. 1A). Much like foams or aerospace honeycomb (Gibson and Ashby 1999), mechanical metamaterials can be created from any base material, and thus can function on many length scales (Fig. 1B). Further engineering of the structure of metamaterials allows for resonant or dampening of acoustic and vibrational characteristics (Fig. 1C, Kadic et al. 2013). In fact, any linear property can be affected by metamaterial engineering, and in some cases nonlinear effects can be controlled as well (Kadic et al. 2019). Multifunctional metamaterials can be designed to shape heat transfer or absorb impact energy (Fig. 1D), and metamaterials can easily be optimized to fit within components that have curved envelopes (Fig. 1E). Without attempting to exhaustively list and subsequently describe what properties can be manipulated, we refer the interested reader to the references herein and give a few representative examples that are pertinent to geothermal applications.

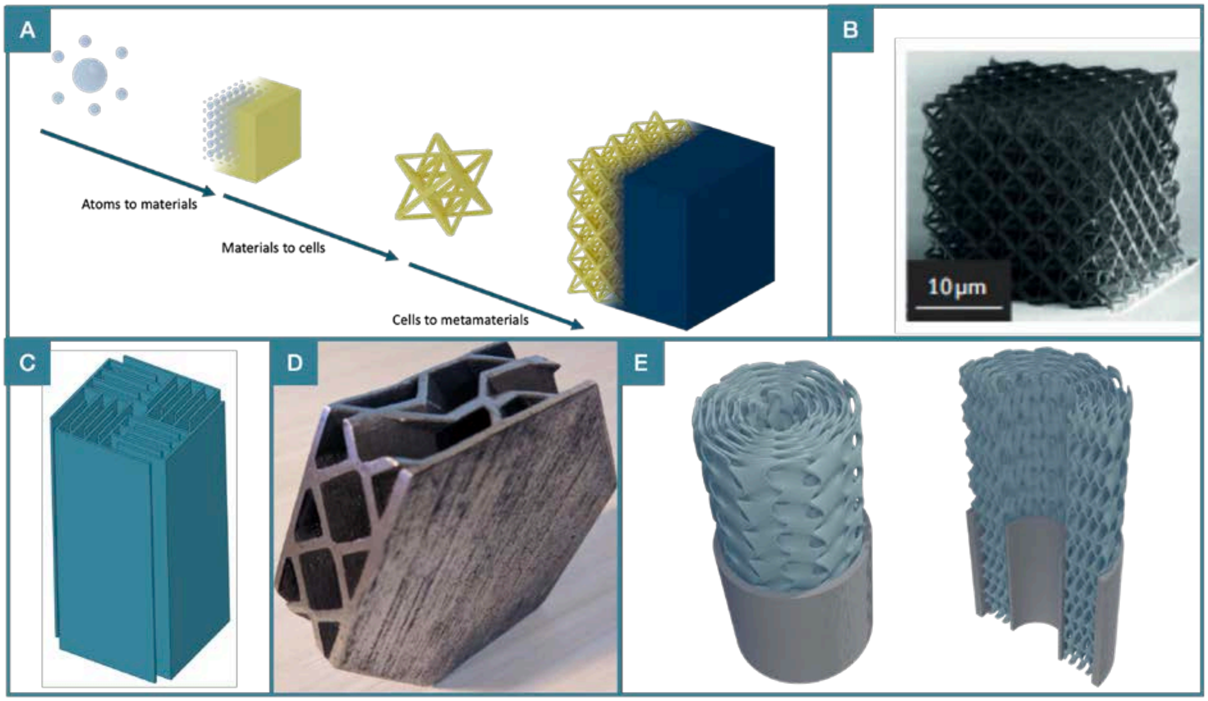


Figure 1: Design and function of mechanical metamaterials. (A) All materials are composed of constituent atoms or molecules, but by structuring those conventional materials using geometry or hierarchy at a "meta" scale additional functionality can be achieved. (B) Since geometry is primarily responsible for the mechanics of a metamaterial, these structures can be fabricated across many different length scales (image reproduced from Kadic et al. 2019). (C) Metamaterials can be created that dampen acoustic or flexural vibrations, and designs can lead to substantial decreases in noise and fatigue in rotordynamic systems (Harne and Wang 2017, Yang et al. 2020). (D) Metamaterials are agnostic to the base material and manufacturing method, so complex shapes can be 3D printed in a variety of substrates; the additively manufactured stainless steel example shown here acts as a structural heat exchanger, efficiently managing heat while also supporting load. (E) Geometries can be designed with virtually any component envelope, so that the functional properties of the lattice can be incorporated into use cases. The example visualized here is designed to be a high shear strength, light-weight tubular component.

2.1 Negative Poisson effect

One of the key characteristics that mechanical metamaterials provide is the ability to generate characteristics that rarely or never appear in naturally occurring materials. The "meiotic" Poisson effect is familiar in most conventional materials, which all have positive Poisson's ratios, indicating that under tension a piece of that material contracts laterally. Architected solids like honeycomb (and mechanical metamaterials in general) can be designed that have *negative* Poisson's ratio, leading to an "auxetic" Poisson effect (Fig. 2A). Auxetic metamaterials have generically longer fatigue life, fracture toughness, and shear strength for materials of comparable stiffness and yield strength (Gibson and Ashby 1999, Francesconi et al. 2020), and the magnitude of this effect can be tuned through geometry alone (Fig. 2B). Examples of this behavior embedded in a cylindrical tubular are shown in Fig. 2C, anticipating the application to geothermally relevant technology in later sections.

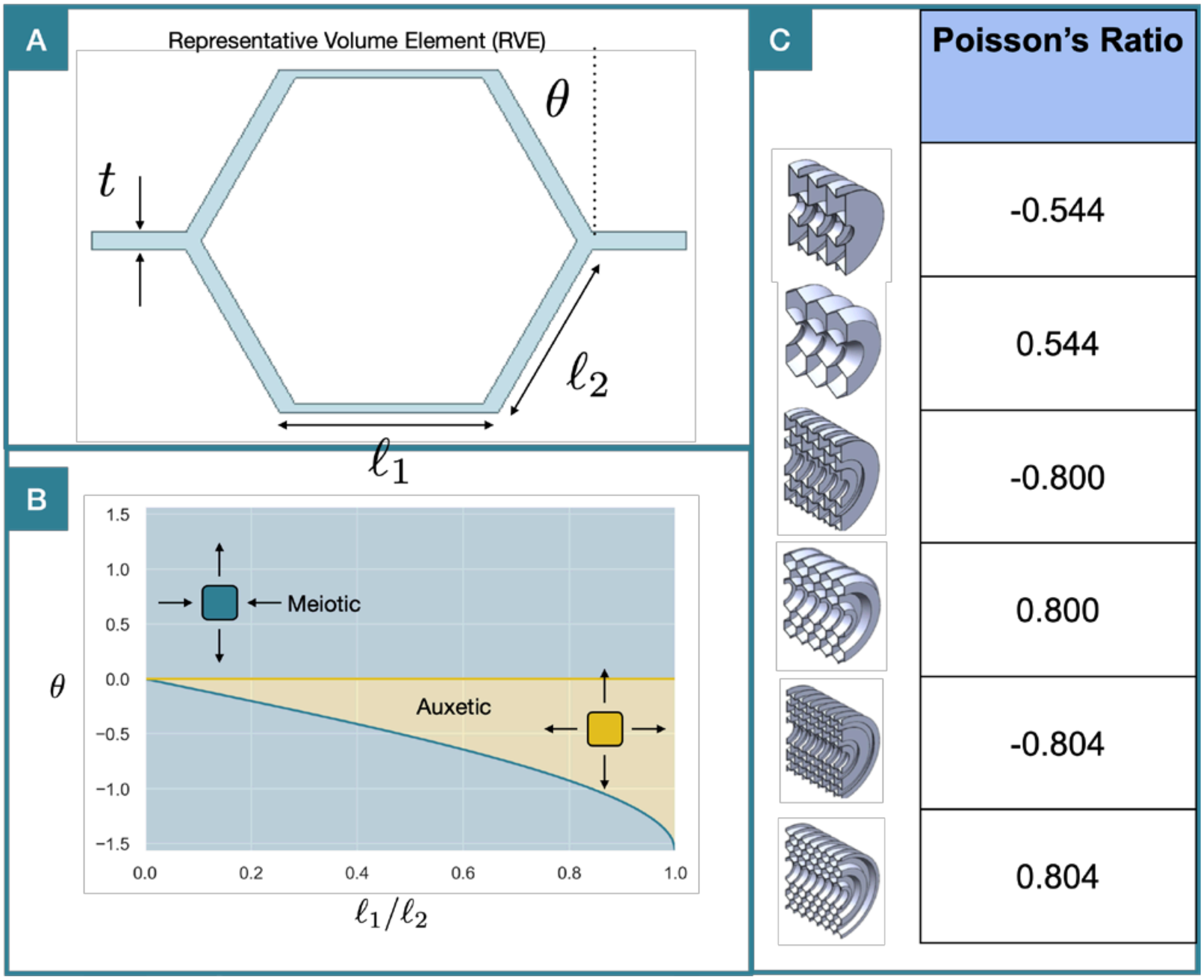


Figure 2: Negative Poisson effect mechanical metamaterials. (A) The representative volume element (RVE) for a honeycomb lattice is determined entirely by lengths of the structure, the thickness of the walls, and the angle of the honeycomb. No matter the base material, if it is composed of an elastic solid, Poisson's ratio in linear elasticity depends only on these geometric factors. (B) By manipulating the angle of the structure, or the ratio of the lengths, standard "meiotic" behavior can be achieved, or the rare "auxetic" behavior. (C) In anticipation of implementing this type of geometry in a geothermal application, embodiments of this geometry in a cylindrical envelope yields the Poisson's ratios shown.

2.2 Tunable thermal expansion

Mechanical metamaterials that are composed of two or more materials arranged in a repeating lattice can be systematically designed to have a tunable effective thermal expansion coefficient, potentially decreasing or even eliminating net thermal strain. The required calculations and geometries are slightly more complex than the auxetic metamaterials in the previous section, but there have been numerous examples of laboratory prototypes that have been additively manufactured, in a variety of different base materials (Yamamoto et al. 2014, Boatti et al. 2017)

Fig. 3 shows how multi-material design can accomplish thermal stability or even negative thermal expansion (NTE) by using specially tuned geometries. Fig. 3A shows a modified honeycomb representative volume element (RVE) that consists of one material with a high coefficient of linear thermal expansion (CLTE) α_1 and another with a low CLTE α_2. As the temperature increases, the inner ribs of the material expand more than the outer members. If the outer members are curved, however, they tend to rotate as a result of the inner rib expansion. Depending on the ratio of the stiffnesses of these two materials, the final effect on the composite can be thermal expansion, contraction, or neither. This 2D RVE can then be radially revolved to create an axisymmetric element as shown in Fig. 2A.

To fully quantify the effective thermal expansion coefficient requires force balance in the lattice, but we choose to use a simplified model to allow us to rapidly determine the efficiency of these designs for creating a thermally stable element. By assuming that the elements of the RVE are composed of pin-jointed members, so that the structure is stress-free after a change in temperature, we may quickly and efficiently calculate the effective thermal expansion. While this is a pathological limit, the essential characteristics of the design can be captured by considering this simple model. The pin-jointed model for the RVE shown is given by (see Jefferson et al. 2009):

$$\frac{\overline{\alpha}}{\alpha_1} = 1 - \left(\frac{\alpha_1}{\alpha_2} - 1\right)\frac{\kappa L_1}{1 - \kappa \mathrm{L}_1 + (\kappa \mathrm{L}_2)^2}$$

Here the inner struts have a thermal expansion coefficient of α_1, the outer members have thermal expansion coefficient α_2, and the curvature of the outer members is given by κ (See Fig. 3A for a schematic). The effective thermal expansion $\overline{\alpha}$ can be positive, negative, or zero, depending on the mismatch between the two materials and the geometry of the lattice.

While this simplified model does not consider the difference in stiffnesses between the two materials, it highlights how geometry and mismatched thermal expansion coefficients can create a multi-material composite that is thermally stable. Fig. 3B shows the qualitative changes in the effective thermal expansion as a function of the bar curvature κ and thermal expansion mismatch α_1/α_2 for values of L_1=4mm and L_2 = 5mm; these lengths were chosen for manufacturability, since these member sizes are well within the tolerances for modern additive manufacturing techniques. For negative or zero curvature, the effective thermal expansion remains positive. For large curvatures or correspondingly large thermal expansion mismatch the thermal expansion coefficient can become negative.

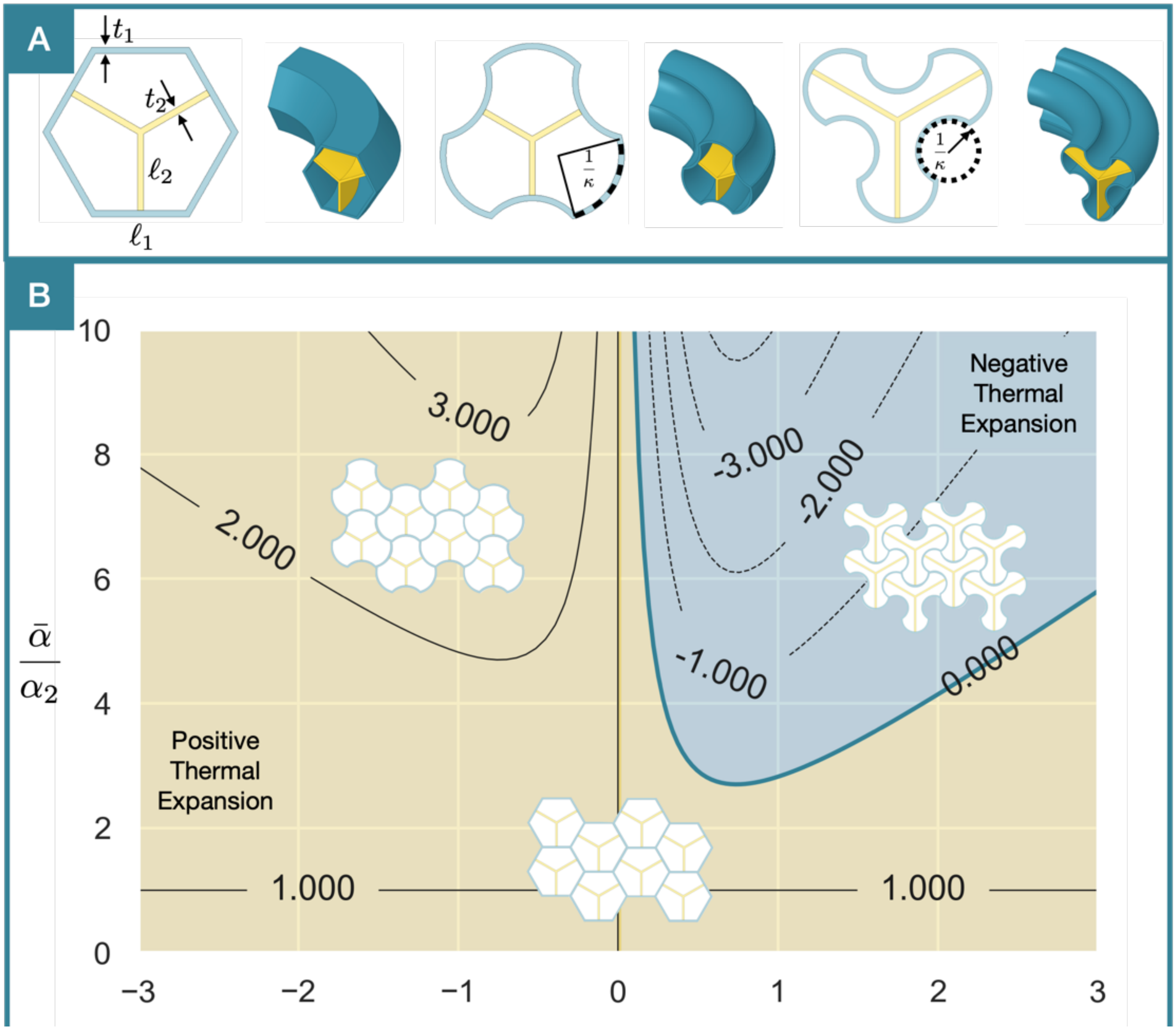


Figure 3: Programmable thermal expansion in metamaterial designs. (A) Modified honeycomb design, with axisymmetric embodiments shown. The internal ribs are defined by a length, a thickness, and a thermal expansion coefficient, while the external members are defined by a length, thickness, thermal expansion, and curvature. (B) Effective thermal expansion as a function of dimensionless curvature, with representative lattice cross-sections shown. For no curvature the effective thermal expansion is just the expansion of the ribs, while changing the curvature can lead to enhanced thermal expansion, negative thermal expansion, or perfect thermal stability.

3. Manufacturing mechanical metamaterials

In the past, the complexity of mechanical metamaterials has limited their use cases to academic studies. Often these geometries require additive manufacturing, and the types and grades of available feedstock then limit the applications for the subsequent parts. Additive manufacturing can be used to create a wide variety of geometries from many different materials but there are fundamental limits on the quantity of parts that could be created in this fashion.

To create mechanical metamaterials at a larger volume, manufacturing that leverages the quick processing of sheet stock with advanced forming and adhesion can be used to create complex parts from relatively simple materials (Fig. 4).

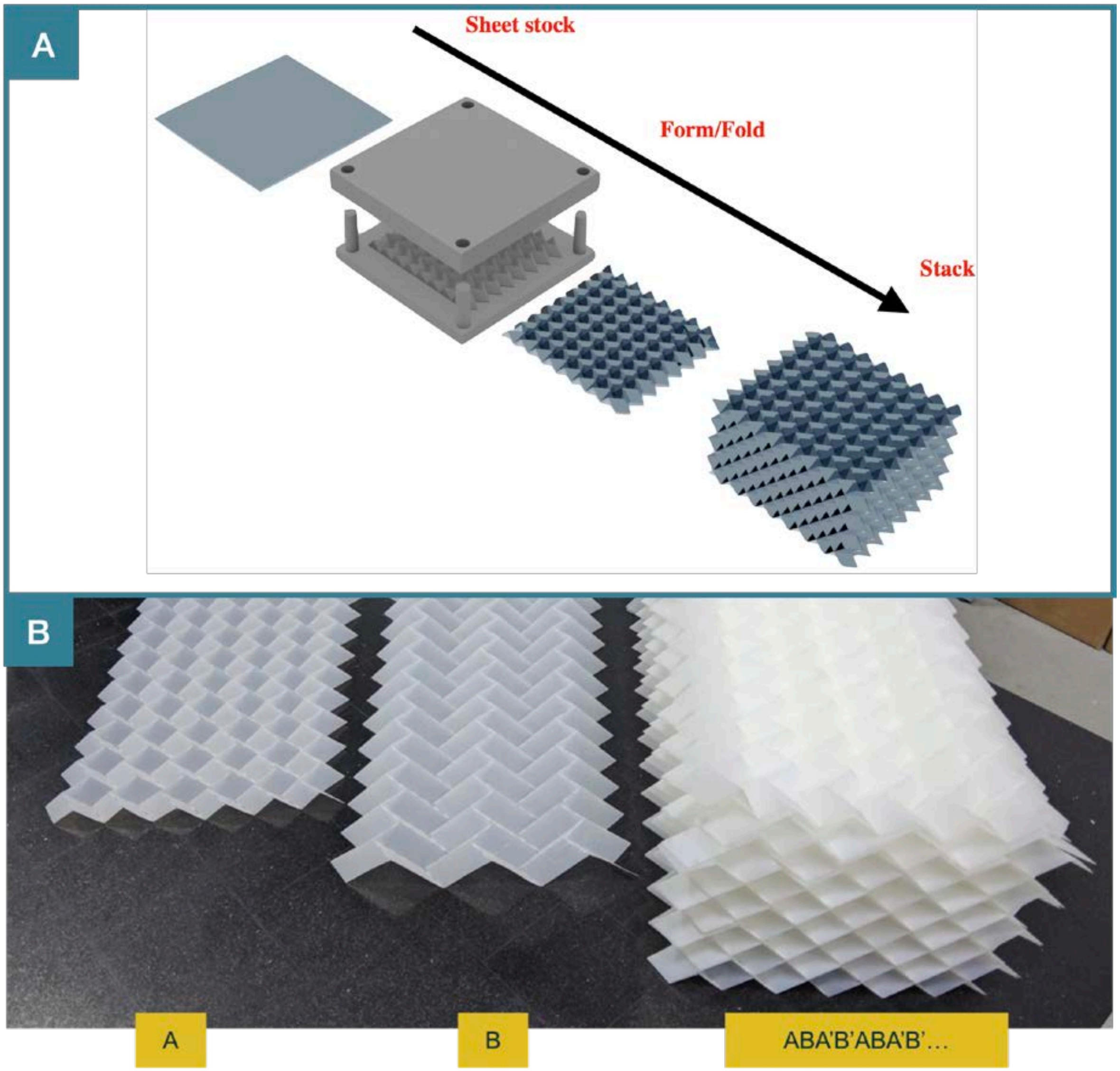


Figure 4: Scalable manufacturing of mechanical metamaterials. (A) Beginning with sheet stock, thermoforming or other compression molding techniques can be applied to fold the sheet into the appropriate shapes, after which the process stacks and adheres the sheets to form a monolithic solid. This process is similar to how honeycomb is manufactured but can be applied to a wide array of geometries. (B) An example of how to form a 3D cellular solid from sheet stock (in this case an engineering thermoplastic).

4. Applications

While the generic potential of mechanical metamaterials is far-reaching, focusing on specific applications that address real problems in EGS is the main goal for this paper. In the following we will discuss prototypes designed to mitigate thermal stresses in EGS wells, as well as potential replacements for sealing technology. We will employ high performance material selection in tandem with mechanical metamaterial engineering. In both examples we find that additive manufacturing enables material usage that would be prohibitively expensive or sub-optimal in other applications.

4.1 Thermal expansion stresses in EGS wells

For an EGS well run to a depth of 5+ km, the operational temperature is at least 200° C and can climb above 350° C in deeper wells. In these environments the cemented casing has no room to thermally expand, and thermal stresses alone can lead to failure of the steel. API-grade steels typically have a CLTE of $\alpha \approx 1.2\ \mu m/m$ °C. Temperature changes induce a pure strain of $\epsilon = \alpha\Delta T$, and this corresponds to a stress of $\sigma = E\epsilon = E\alpha\Delta T$, where E is stiffness of the casing steel and ΔT is the change in temperature from ambient to operational.

Because the casing cannot freely expand, thermal expansion stress sets a maximum operating temperature based on the yield stress of the casing. For example, at ΔT = 160 °C API-grade K55 steel yields without any external load, whereas L80 can operate up to 230°C. When the casing yields, as the well cools the casing is left in a state of residual tension (Fig. 5A). In order to alleviate this problem higher strength alloys are required, which can be problematic since high grade steels may not meet corrosion-resistant standards and can be prohibitively expensive (Fig. 5B).

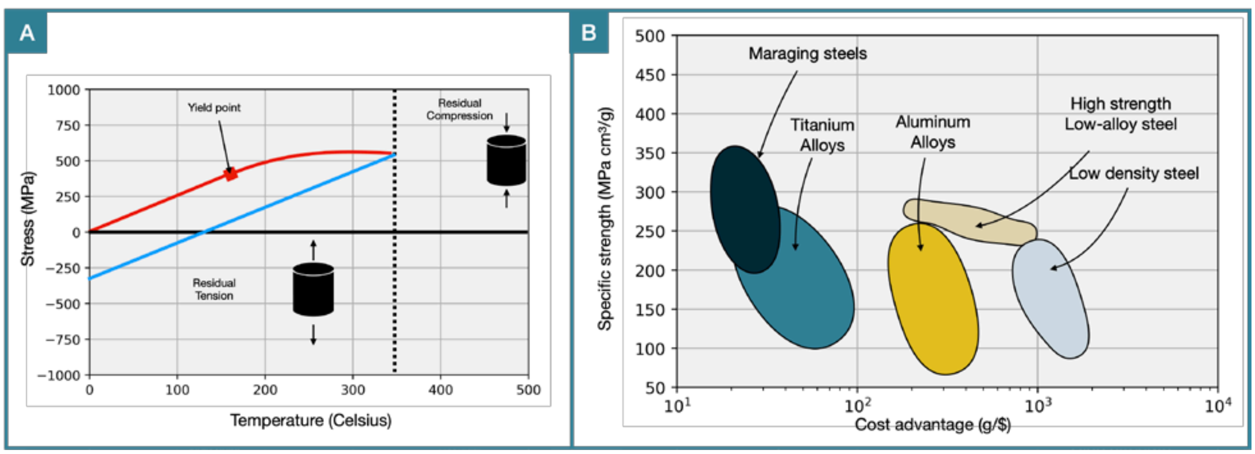


Figure 5: Thermal stresses in conventional steel casing. (A) Without properly accounting for thermal expansion, legacy casing steel will fail. As the well heats up the casing is constrained and undergoes temperature-induced compression. As the well cools the casing is left in a state of residual tension, which ultimately weakens the casing against external loads and pressures. (B) A wide range of alloys are available with the strength to withstand EGS conditions, but most are prohibitively expensive.

Instead of using higher strength steels, allowing the system to expand under thermal cycling could solve the issue. Pipe systems on the surface generally accommodate thermal expansion stresses with a bellows expansion joint. These allow thermo-mechanical strain to occur without inducing adverse stresses. In contrast, couplings and connectors in the casing string are gas-tight threaded collars that have no ability to deform. Incorporating a flexible connector into the installation of the casing would mitigate thermal expansion stresses and ultimately improve the lifetime and viability of an EGS well (Thorbjornsson et al. 2019). Unfortunately, traditional metal expansion joints suffer drawbacks in regard to deployment for EGS casing application: (1) the annular clearance required for a bellows is prohibitive; (2) the collapse pressure for conventional bellows is low compared to the requirements for EGS; and (3) they are compliant to both shear and bending, which is not ideal for a casing string connector.

Mechanical metamaterial engineering can be used to produce a flexible connector (Geometrically Enhanced Metamaterial Flexible connector, or GEM-Flex) that could not be created using conventional manufacturing or design methods (see Fig. 6A). This casing connector is uniquely qualified to accommodate thermal expansion in the casing string while remaining capable of bearing the large axial and pressure loads associated with EGS. It is designed to be additively manufactured from a high strength maraging steel that would be prohibitively expensive and nearly impossible to machine using traditional manufacturing methods. The component’s flexibility arises from its complex geometry, and additive manufacturing lowers cost barriers to high-performance materials. Many high-performance materials come with a cost that make them economically unviable for use in the downhole environment. For example, titanium alloys and maraging steels would make the perfect choice for casing tubing, except for the price tag of at least $50/kg, which is an order of magnitude more expensive than conventional API-grade alloys (Fig. 5B). Using additive manufacturing cuts down on wasted material that would be lost to milling and allows high strength materials to achieve their potential in carefully designed parts.

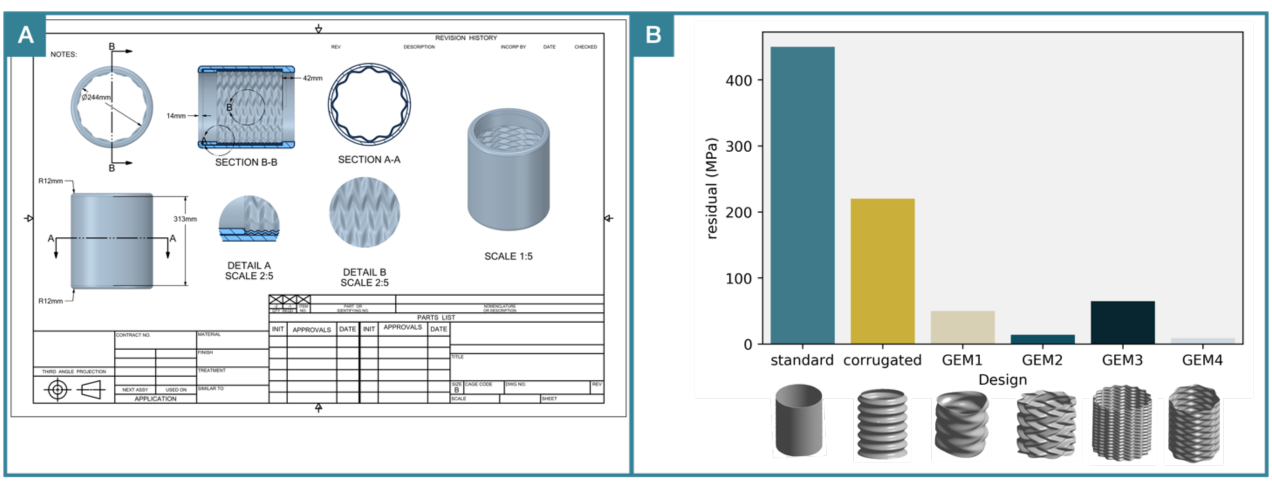


Figure 6: Geometrically enhanced metamaterial flexible connector (GEM-Flex). (A) Technical schematic for GEM-Flex. Dimensions displayed are for a 9-5/8” outer diameter casing. (B) Geometric optimization of tubular shapes determines the number of azimuthal and axial convolutions as well as pitch and amplitude of corrugations. Parametric analysis is performed on the GEM-Flex interior surface to determine which geometry performs best when compared to L80 tubulars and L80 corrugated bellows. Shown here is the simulated residual stress in the part after thermal loading from 22°C to 350°C and back.

Fig. 6A shows a prototype EGS casing connector designed to be manufactured in Grade 300 maraging steel to interface with a threaded 9-5/8 " outer diameter production casing with dimensions allowing clearance for cementing between production and intermediate casing. These dimensions are chosen to align with common elements of an EGS production casing, although adaptation to 7” production casing would not invalidate the design methodology. The upper surface of the design connects directly to a multi-corrugated surface that has been designed to deform appreciably in the axial direction, while remaining relatively rigid under other loads. This multi-corrugated surface is housed within a smooth annular exterior. The gap between the surfaces along with the complex corrugated geometry is not possible using conventional manufacturing. The multi-corrugated surface texture is generated from numerous superimposed convolutions with a helical pitch designed to optimize the flexibility of the connector in the axial direction, while preventing plastic collapse. Finite element analysis using nonlinear constitutive models for high strength steels are used to compare standard geometries to the GEM-Flex multi-corrugation design. When compared to cylindrical pipes or singly corrugated bellows (Fig. 6B), these geometries tend to spread stress throughout connector, instead of focusing in one region that leads to eventual collapse or buckling failure. The multi-corrugated maraging steel surfaces GEM1 – GEM4 perform substantially better when run through the same thermal cycling by ending with much lower residual stresses. These lower residual stresses mean the connector provides a greater burst resistance to pressure since there is less overall load, and thus less chance of ultimate failure.

We built on these initial parametric design optimization studies to examine how a standard connector and the most promising GEM structure would perform when loaded under more realistic conditions (Fig. 7). These FEA simulations included two L-80 steel casing segments connected to one another and fully encased in concrete. To model the L80 steel we use an empirically determined bilinear kinematic hardening law with temperature-dependent yield strength. We simulated the heat-up of a region of casing segment from 22 °C to 350 °C, and then measure the residual stress in the entire pipe assembly after cool-down. We found the residual stress in a pure L80 casing segment with traditional connector is 440 MPa, whereas the GEM-Flex augmented system has a residual stress of 160 MPa, which is a nearly 3-fold reduction in the casing stress.

4.2 Mitigating elastomeric failure in EGS conditions

Elastomeric materials are involved in nearly every downhole tooling component and are especially important for maintaining a high differential pressure in a sealing system. Unfortunately, most elastomers are unstable above 180° C, and are incapable of surviving the EGS environment. Even high temperature engineering products like the fluoro-elastomer AFLAS is subject to corrosion and subsequent chemical degradation that leads first to decreased performance and ultimately to catastrophic failure (Fig 8).

Ideally elastomers could be replaced with a material that can handle corrosive compounds and extreme temperatures, but there are several key properties that elastomers exhibit. A high bulk modulus, leading to nearly incompressible behavior, is a vital ingredient for a sealing element, while large elongation at break is almost equally important. These mechanical characteristics are all temperature-dependent, however, and it is clear that conventional elastomers do not perform their required functions at EGS temperatures.

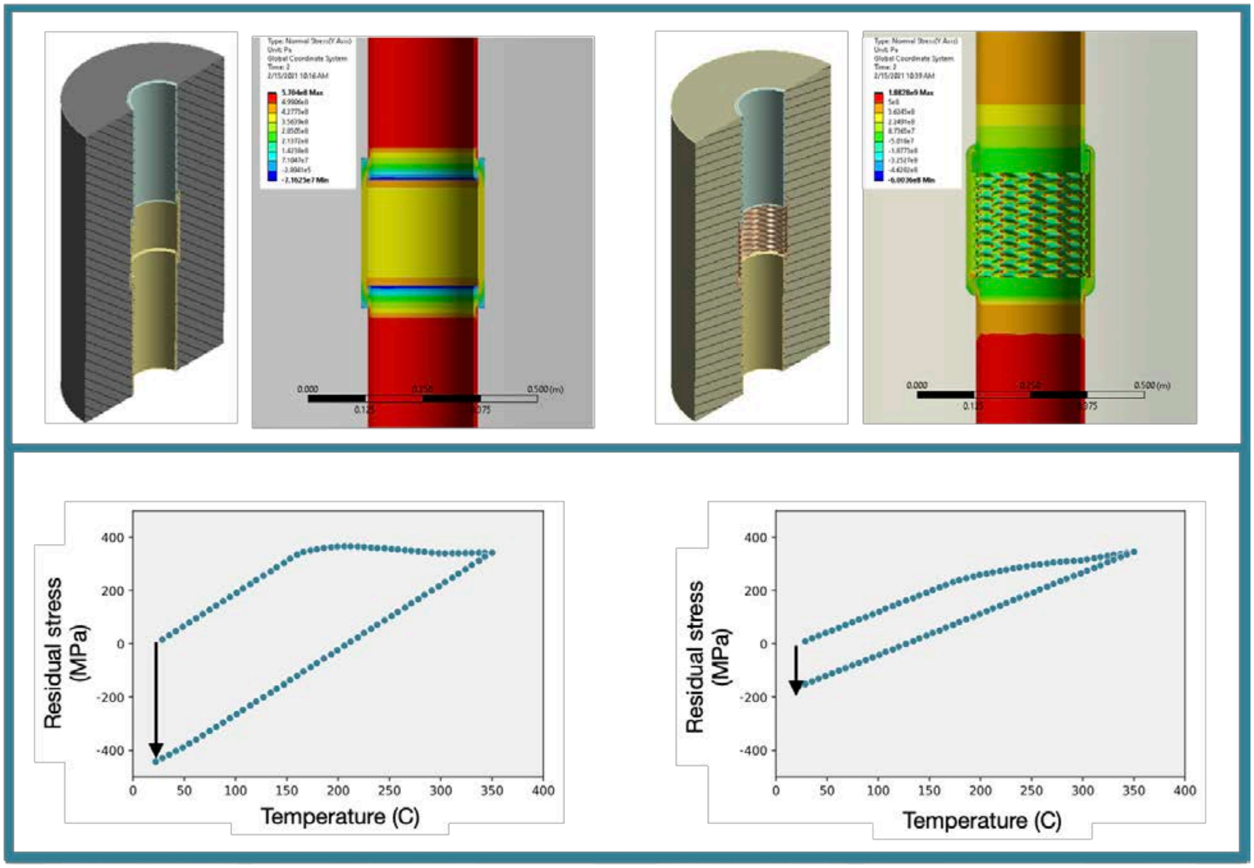


Figure 7: Finite element analysis comparison between standard casing and GEM-Flex enhanced casing. Full stress analysis is performed on a standard L80 casing segment and associated axial connector, with a cement sheath, and compared to the same set-up with the connector replaced with GEM-Flex. In comparing the stress history of the L80 casing with the GEM-Flex augmented system we see a residual stress of 440 MPa in the standard system, with a massive reduction to 160 MPa in the augmented system.

Figure 8: A packer for use in zonal isolation is a clear case study of elastomeric failure, seen here before and after downhole deployment. The "shoulder" produced by seal extrusion is a clearly visible pain-point for EGS well operation. Images courtesy of Prof. John McLennan.

We will focus on a packer element for zonal isolation as the archetypal component to replace. Instead of creating a better elastomer, which requires advanced chemical and molecular formulations, an ideal element would be composed of a material that satisfies all chemical, thermal, and mechanical objectives simultaneously. To achieve these goals, metamaterial engineering can be used to imbue a chemically resistance, high performance material with the appropriate mechanical properties that a packer element requires. Consider the thermoplastic polyether-ether-ketone (PEEK), for example (Fig. 9). PEEK is a stiff plastic at room temperature, but at higher temperatures undergoes a glass transition and becomes more malleable. Fig. 9 shows temperature-dependent properties of several commercially available PEEK formulations compared to elastomers. As the temperature ramps up, elastomers become more brittle and PEEK becomes more ductile, and even overcoming the strain at break for elastomers at EGS-relevant temperatures. A solid coupon of PEEK is still many times stiffer than an elastomer, however, and thus requires metamaterial engineering to make it more compliant.

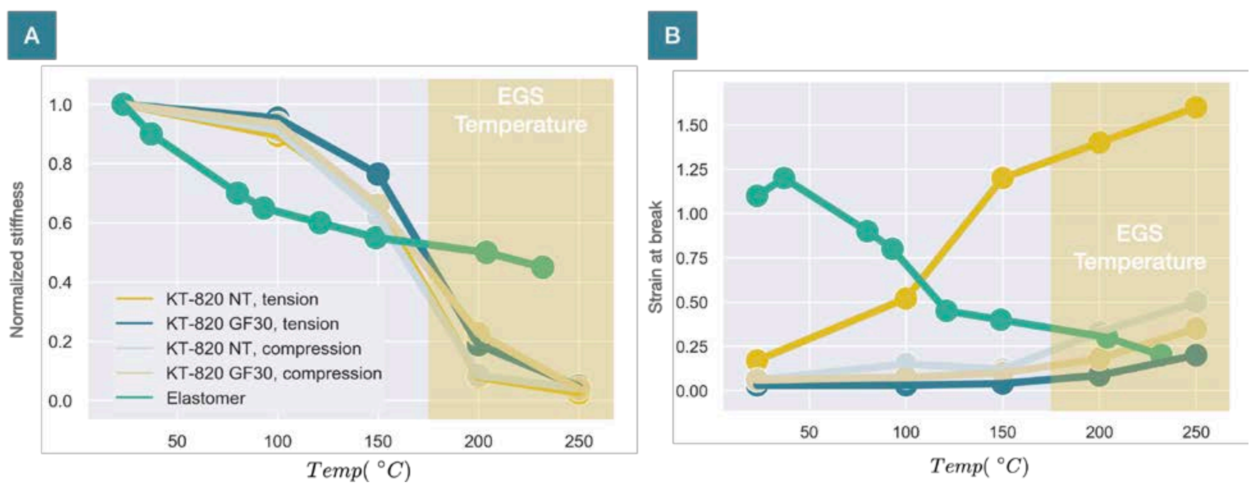
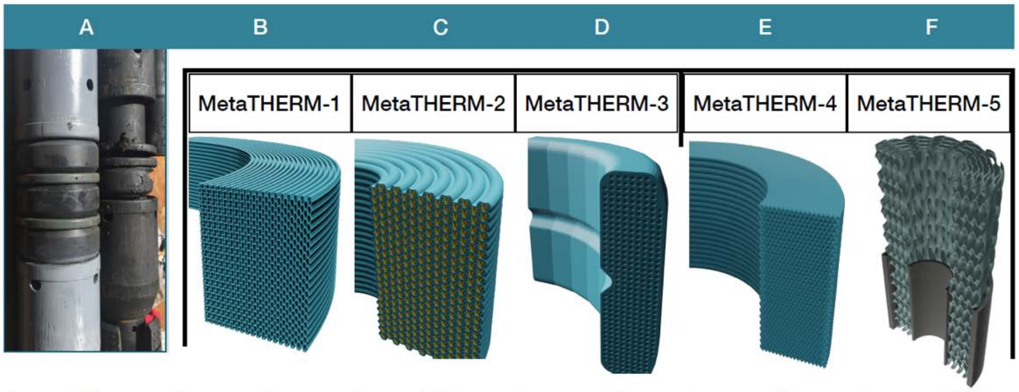


Figure 9: Thermomechanical comparison of PEEK and elastomers. (A) An apparent disadvantage for using hard thermoplastics to replace elastomers is the high stiffness. However, at EGS temperatures this stiffness drops dramatically, and with further design can be lowered further without sacrificing strength. (B) Elongation at break for unfilled PEEK, fiber-reinforced PEEK, and elastomers. At low temperatures, elastomers have large elastic recoverability, whereas PEEK is brittle. At EGS temperatures, however, elastomers become brittle and PEEK becomes ductile. Consequently, PEEK achieves better mechanical properties at high temperatures when compared to elastomers.

We propose five separate prototype geometries (which we deem “MetaTHERM”) that have characteristics designed to mitigate elastomer failure at high temperatures by embedding geometry within solid PEEK (Fig. 10), and briefly describe their functioning below.



	A	B	C	D	E	F
VPR	✗	✓	✗	✓	✓	✗
VTE	✗	✗	✓	✗	✗	✗
Stress Guides	✗	✗	✗	✓	✗	✓
Deployable	✗	✓	✗	✓	✓	✗
Compliant	✓	✓	✓	✓	✓	✓
High Temperature	✗	✓	✓	✓	✓	✓
High Pressure	✗	✓	✓	✓	✓	✓
Molded and stacked	✓	✓	✗	✗	✓	✗
Additively manufactured	✗	✓	✓	✓	✓	✓
Chemically resistant	✗	✓	✓	✓	✓	✓

Figure 10: The five families of MetaTHERM and how they qualitatively compare against conventional packer elements. The table shows the relative benefits and drawbacks from each proposed design. In general, high temperature, high pressure, and chemical resistance follow from using PEEK instead of elastomers, while the other characteristics arise from the designs themselves. (A) Elastomeric packer elements are composed of a solid ring or collar that degrades above 150°C, fails catastrophically in the presence of highly corrosive solvents, and in many cases cannot hold the required pressure differential due to a low modulus. Elastomers are very compliant, however, requiring a small setting force to seat on the support ring structure, and can be molded and deployed as an array (shown here in a conventional three-ring stack). (B) The Variable Poisson Ratio (VPR) design is composed of a radially graded cellular pattern that is highly compliant and has a tunable Poisson effect. (C) The VTE design require two materials with different coefficients of thermal expansion to function but is structurally similar to the VPR design. (D) A macro-porous element has cavities introduced into the body of the design to increase compliance, modify Poisson's ratio, and guide internal stresses. The pattern of pores will determine the effectiveness of the element as a seal. (E) Origami-inspired design element for maximum deployability. (F) Complex surface design to concentrate stress fractures away from vital parts of the element.

4.2.1 MetaTHERM-1

MetaTHERM-1 uses RVEs that generate a radially variable Poisson effect, so that when the tubular element is compressed or tensioned the internal radius neither expands nor contracts, but the sealing surface is still available to expand regularly. This Variable Poisson's Ratio (VPR) material can also be tuned so that it expands in either compression or tension, so that it may be customized to a particular mechanically-set packer system. The VPR effect is achieved by varying the unit cell geometry, which is based on a honeycomb, but implemented in a cylindrically symmetric fashion. It is a cellular solid that has a high strength-to-weight ratio, and is relatively compliant when constructed out of a high stiffness thermoplastic because of the thin-walled construction

4.2.2 MetaTHERM-2

MetaTHERM-2 is a multi-material solution that uses a specially designed RVE to produce a Variable Thermal Expansion (VTE) effect, as described in Section 2.2 above. Layering two or more materials with disparate thermal expansion coefficients can produce ultralow thermal expansion in materials (Yamamoto et al. 2014) and composite lay-ups can combine materials with exotic geometries to produce exotic thermal expansion properties.

4.2.3 MetaTHERM-3

MetaTHERM-3 strategically introduces macropores into the element to soften the part and enable advantageous buckling and compliance for sealing conditions. Patterning of macropores within elastomeric or ductile materials is well-established in the literature (Matsumoto and Kamien 2009, Bar-Sinai et al. 2020), and even though the subtraction of material can lead to stress focusing in traditional analysis, the overall load required to compress the metamaterial is lower. Consequently, the fatigue life of the component generally increases (Francesconi et al. 2020).

4.2.4 MetaTHERM-4

MetaTHERM-4 is designed to be maximally deployable. These stackable elements are similar to existing V-stacks or other cylindrical sealing elements but are designed to maximally leverage the Poisson effect to deploy over a wide range of borehole sizes. Additionally, these stackable elements have no preferred orientation, unlike traditional V-stacks. The parameters associated with these expandable designs arise from origami-inspired RVEs, as well as deployable structures that have been used in a variety of other applications (You and Kuribayashi 2009, Zirbel et al. 2014).

4.2.5 MetaTHERM-5

Finally, MetaTHERM-5 is designed to minimize the fracture paths that nucleate within the element during operations. Simply by changing the shape of the surface, the severity of fractures can be controlled and mitigated. The propagation of fracture and cracks in the downhole environment is well studied (Jaeger et al 2009), but the mitigation of fracture in lattice-materials and curved surfaces can also be applied to material components like a packer element (Vaziri and Mahadevan 2008, Evans and Levine 2013, Bende et al. 2015, Tankasala and Fleck 2020).

5. Conclusion

Mechanical metamaterials can add value to current tools and imbuing existing conventional materials with properties that are usually inaccessible. We have only given the most cursory overview of what geometry can accomplish and have suggested several use cases based on the current state of the art of metamaterial engineering. Other applications with vibrational control, heat management, and even flow control is likely to be of interest in the future.

Future work on mitigating thermal expansion stresses using the GEM-Flex prototype is already underway. Working with collaborators we have begun fabricating maraging steel additively manufactured prototypes with a Laser Powder Bed Fusion system and anticipate high temperature measurements to be performed soon. These validation experiments will not only inform on our design choices but give valuable information on the process control associated with additively manufacture high performance materials.

High temperature elastomer replacements for packer elements are only one of the many applications for sealing technology associated with mechanical metamaterials. A static seal is the most clearly applicable based on our preliminary research, but additional dynamic applications are on the horizon.

Acknowledgement

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