# *Elastocaloric and Solid-State Cooling Materials: A Review on Emerging Refrigeration Technologies*

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### *ABSTRACT*

*Conventional vapor compression refrigeration systems are widely used but they consume high energy and use refrigerants that are harmful for environment. In recent years, researchers are focusing on solid-state cooling technologies which can replace traditional refrigeration methods. Among different solid-state cooling approaches, elastocaloric effect is gaining more attention due to its high efficiency and eco-friendly nature. Elastocaloric materials show temperature change when mechanical stress is applied and removed. Shape Memory Alloys (SMAs), especially Ni-Ti based alloys, are widely studied for this purpose. This paper reviews the fundamentals of elastocaloric effect, working principles, important materials, performance parameters, advantages, limitations and recent developments in this field. Different materials such as SMAs, natural rubber, and polymers are discussed. Comparison with other solid-state cooling methods like magnetocaloric and electrocaloric cooling is also presented. Challenges and future scope of elastocaloric cooling systems are highlighted.*

***KEYWORDS:*** *Elastocaloric effect, Solid-state cooling, Shape Memory Alloys, NiTi, Refrigeration, Eco-friendly cooling*

## INTRODUCTION

Refrigeration and air-conditioning are essential part of modern life. Most of the systems today work on vapor compression cycle which uses refrigerants like CFCs, HCFCs and HFCs. These gases causes ozone depletion and global warming. Due to environmental regulations and increasing energy demand, new cooling technologies are required.

Solid-state cooling is an alternative which does not use harmful gases. Instead, it uses physical properties of materials to produce cooling effect. Among these, elastocaloric cooling is based on stress-induced temperature change in materials. This phenomenon is seen mainly in Shape Memory Alloys (SMAs).

Elastocaloric materials can show large temperature changes (up to 20 K) when subjected to cyclic loading and unloading. Because of this, they are considered promising for next generation refrigeration systems.

## PRINCIPLE OF ELASTOCALORIC EFFECT

The elastocaloric effect is a thermo-mechanical phenomenon in which a material undergoes a reversible temperature change when it is subjected to mechanical loading and unloading. This effect is strongly associated with materials that exhibit stress-induced phase transformations, especially **Shape Memory Alloys (SMAs)** such as NiTi (Nitinol). The underlying reason for this behavior is the coupling between **mechanical stress, crystal structure, and entropy** of the material.

### 1. Phase Transformation in Shape Memory Alloys

SMAs exist mainly in two solid phases:

- **Austenite phase** – high temperature, more ordered and symmetric crystal structure.
- **Martensite phase** – low temperature, less symmetric and easily deformable structure.

Under normal conditions, the transformation between these two phases occurs due to temperature change. However, in elastocaloric materials, this transformation can also be **triggered by mechanical stress** at nearly constant temperature.

When stress is applied to the austenite phase, the material transforms into martensite even without cooling. This is called **stress-induced martensitic transformation**. During this transformation, the internal arrangement of atoms changes, leading to a release of latent heat.

**2. Heating During Loading (Exothermic Process)**

- Initially, the SMA is in austenite phase.
- Mechanical stress is applied rapidly (adiabatic condition).
- Austenite transforms into martensite.
- Due to decrease in entropy and structural rearrangement, **heat is released**.
- The temperature of the material increases.

This is why the material becomes warmer when stretched or loaded.

**3. Cooling During Unloading (Endothermic Process)**

- When the stress is removed, martensite becomes unstable.
- The material reverts back to austenite phase.
- To regain the original structure, the material **absorbs heat from surroundings**.
- This leads to a drop in temperature below the initial value.

This cooling is the useful part of the elastocaloric cycle for refrigeration purposes.

**4. Adiabatic and Reversible Nature**

For a significant elastocaloric temperature change to occur, the loading and unloading must be **adiabatic**, meaning no heat exchange with surroundings during the process. Also, the phase transformation should be **reversible** for repeated cycles, which is a key property of SMAs.
Because no permanent deformation occurs, the material can undergo thousands to millions of cycles, making it suitable for cooling devices.

**5. Thermodynamic Explanation**

The elastocaloric effect can be explained using thermodynamic principles. The temperature change is related to entropy change and applied stress.
A simplified relation is:
ΔT=−TρCp(∂S∂σ)Δσ\Delta T = - \frac{T}{\rho C_p} \left( \frac{\partial S}{\partial \sigma} \right) \Delta \sigmaΔT=−ρCpT(∂σ∂S)Δσ
Where:

- ΔT\Delta TΔT = Adiabatic temperature change

- TTT = Absolute temperature
- ρ\rhoρ = Density of material
- CpC_pCp = Specific heat at constant pressure
- SSS = Entropy
- σ\sigmaσ = Applied stress

This equation shows that larger entropy change during phase transformation results in larger temperature change.

**6. Stress–Strain and Temperature Response**

During loading, the stress–strain curve of SMA shows a plateau region. This plateau corresponds to the phase transformation. In this region:

- Strain increases without significant increase in stress.
- Temperature rises sharply due to latent heat release.

Similarly, during unloading, the reverse plateau is seen with temperature drop.

## SOLID-STATE COOLING TECHNOLOGIES OVERVIEW

Solid-state cooling refers to refrigeration methods that do **not** rely on vapor compression, refrigerant gases, or fluid phase change. Instead, these technologies use the intrinsic thermo-physical response of materials when exposed to external fields such as **magnetic field, electric field, mechanical stress, or pressure**. The cooling effect is produced due to **entropy change** and **reversible phase transformation** inside the solid material.

These methods are often called **caloric cooling technologies** because the cooling is associated with caloric effects in materials.

**1. Basic Concept of Caloric Effects**

When an external stimulus is applied to certain functional materials, their internal order changes. This change in order leads to variation in entropy. Under adiabatic conditions, this entropy change results in a **temperature change**.

General idea:

- Apply external field → entropy decreases → temperature increases (heating)
- Remove field → entropy increases → temperature decreases (cooling)

This principle is common for all solid-state cooling methods.

***Table 1: Solid-state cooling includes different effects***

| Effect | Stimulus Applied | Example Material | Cooling Mechanism |
|---|---|---|---|
| Magnetocaloric | Magnetic field | Gadolinium | Entropy change due to magnetic ordering |
| Electrocaloric | Electric field | Ferroelectric ceramics | Polarization change |
| Barocaloric | Pressure | Plastic crystals | Volume change |
| **Elastocaloric** | Mechanical stress | NiTi alloys | Phase transformation |

## MATERIALS SHOWING ELASTOCALORIC EFFECT

The success of elastocaloric cooling technology mainly depends on the **choice of material**. Not all materials show significant temperature change under mechanical loading. Only those materials which undergo **reversible structural or molecular rearrangement** with large entropy change are suitable for elastocaloric applications.

These materials are generally classified into three main groups:

1. **Shape Memory Alloys (SMAs)**
2. **Elastomers such as Natural Rubber**
3. **Polymers and Composite Materials**

Each category has different working mechanism, advantages and limitations.

### 1. Shape Memory Alloys (SMAs)

Shape Memory Alloys are the most promising and widely researched elastocaloric materials. Their elastocaloric behavior is due to **stress-induced martensitic phase transformation**.

**NiTi (Nitinol)**

NiTi alloy is considered the best elastocaloric material because of its superior thermo-mechanical properties.

**Important characteristics:**

- Large reversible strain: **6–8%**

- High adiabatic temperature change: **15–20 K**
- Excellent fatigue resistance (millions of cycles)
- Good thermal conductivity compared to polymers
- Stable and repeatable phase transformation

When tensile stress is applied to NiTi in austenite phase, it transforms into martensite and releases latent heat. On unloading, reverse transformation occurs and cooling is produced.
NiTi wires, thin plates and tubes are commonly used in experimental elastocaloric cooling devices.

**Cu-Based Shape Memory Alloys**
Other SMAs like **Cu-Zn-Al** and **Cu-Al-Ni** also show elastocaloric effect.
**Advantages:**

- Lower cost compared to NiTi
- Easy to manufacture

**Limitations:**

- Lower fatigue life
- Brittle nature
- Smaller temperature change (10–15 K)

Because of brittleness, they are less preferred for repeated mechanical cycling.

**Fe-Based SMAs (Emerging)**
Recent research is also exploring **Fe-Pd** and **Fe-Rh** alloys for elastocaloric applications, but these are still under development.

**2. Natural Rubber**
Natural rubber is an elastomer that shows elastocaloric effect due to **entropy change in polymer chains** during stretching and releasing.
**Working Mechanism**

- Rubber consists of long polymer chains in random arrangement.
- When stretched, the chains become aligned, decreasing entropy and releasing heat.
- When released, chains return to random state, absorbing heat and causing cooling.

This effect is known as **entropic elastocaloric effect**, different from phase transformation in SMAs.

**Properties of Natural Rubber**

- Very large strain capability: up to **300–500%**
- Very low cost and easily available
- Excellent fatigue life
- Environment friendly and biodegradable
- Temperature change: **5–8 K**

Although the temperature change is smaller than SMAs, rubber is attractive for low-cost cooling devices.

### 3. Polymers and Polymer Composites

Some synthetic polymers also exhibit elastocaloric effect due to molecular orientation during deformation.

Examples include:

- Polyurethane elastomers
- Silicone rubbers
- Thermoplastic elastomers

These materials show moderate temperature change but are still in research stage.

**Polymer Composites**

To improve performance, researchers are developing composites by adding:

- Carbon nanotubes
- Graphene particles
- Metallic fillers

These additives improve:

- Thermal conductivity
- Mechanical strength
- Heat transfer rate

However, practical application is yet to be achieved.

## WORKING CYCLE OF ELASTOCALORIC COOLING SYSTEM

The basic cooling cycle includes four steps:

1. Adiabatic loading – temperature increases
2. Heat rejection to surroundings
3. Adiabatic unloading – temperature drops
4. Heat absorption from space to be cooled

This cycle repeats similar to refrigeration cycle but without refrigerant.

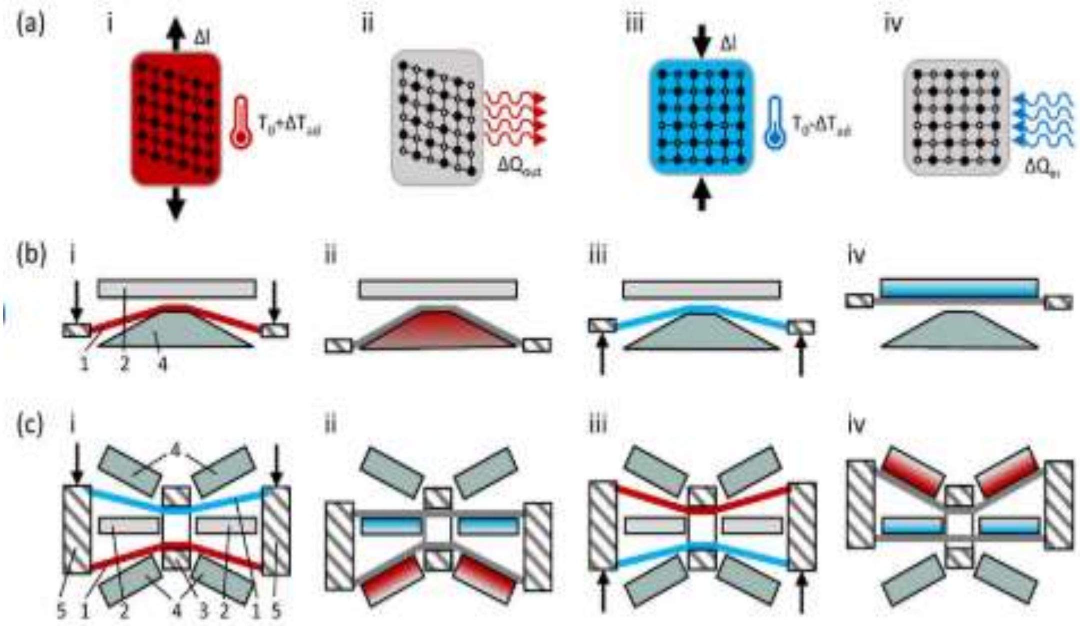


***Figure 1: Elastocaloric Cooling Cycle***

## PERFORMANCE PARAMETERS

Important parameters for elastocaloric materials:

- Adiabatic temperature change (ΔT)
- Isothermal entropy change (ΔS)
- Fatigue life
- Mechanical strength
- Thermal conductivity

| Material | ΔT (K) | Strain (%) | Fatigue Life |
| --- | --- | --- | --- |
| NiTi | 18–20 | 6–8 | High |
| Cu-Al-Ni | 12–15 | 4–6 | Medium |
| Natural Rubber | 5–8 | 300 | Very High |

## ADVANTAGES OF ELASTOCALORIC COOLING

- No harmful refrigerants
- High energy efficiency
- Compact design
- Silent operation
- Environment friendly
- Potential for miniaturization

## LIMITATIONS AND CHALLENGES

Despite advantages, there are challenges:

- Material fatigue due to cyclic loading
- High cost of NiTi alloys
- Need for efficient mechanical loading system
- Heat transfer management
- Scalability issues for large systems

## COMPARISON WITH CONVENTIONAL REFRIGERATION

| Feature | Vapor Compression | Elastocaloric Cooling |
| --- | --- | --- |
| Refrigerant | Required | Not required |
| Environmental impact | High | Very low |
| Noise | Moderate | Low |
| Efficiency | Moderate | High (potential) |
| Maintenance | High | Low |

## RECENT RESEARCH AND DEVELOPMENTS

Recent studies focus on:

- Improving fatigue life of SMAs
- Developing thin wire and film forms
- Use of regenerative heat exchangers
- Prototype elastocaloric refrigerators
- Hybrid cooling systems

Researchers have developed small prototype refrigerators using NiTi wires showing promising results.

## APPLICATIONS

Elastocaloric cooling can be used in:

- Domestic refrigeration
- Air conditioning
- Electronic cooling
- Medical storage systems
- Space applications

## FUTURE SCOPE

Future work is needed in:

- Low cost SMA production
- Advanced mechanical actuation systems
- Integration with renewable energy
- Commercial scale prototypes

Elastocaloric technology may replace traditional refrigeration in coming decades.

## CONCLUSION

Elastocaloric and solid-state cooling materials offers a new direction for refrigeration technology. With increasing environmental concerns, this method is eco-friendly and efficient alternative. Shape Memory Alloys like NiTi shows excellent potential due to large temperature change and good mechanical properties. Although challenges like fatigue and cost are present, ongoing research is improving the feasibility of this technology. In near future, elastocaloric cooling systems may become common in refrigeration and air conditioning applications.

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