INTERNATIONAL JOURNAL OF REFRIGERATION 54 (2015) 88–97

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/ijrefrig

Scientific test setup for investigation of shape memory alloy based elastocaloric cooling processes

Marvin Schmidt [a,b,*], Andreas Schütze [a,1], Stefan Seelecke [b,2]

[a] Lab for Measurement Technology, Department of Mechatronics Engineering, Saarland University, Campus A 5.1, 66123 Saarbrücken, Germany

[b] Multifunctional Materials Systems Lab, Department of Mechatronics Engineering, Saarland University, P. O. Box 151150, 66041 Saarbrücken, Germany

ARTICLE INFO

Article history:
Received 1 November 2014
Received in revised form
4 February 2015
Accepted 1 March 2015
Available online 10 March 2015

Keywords:
Shape memory alloys
Elastocaloric refrigeration
Cooling
Latent heats
Phase transformation

ABSTRACT

Solid state refrigeration processes, such as magnetocaloric and electrocaloric refrigeration, have recently shown to be promising alternatives to conventional compression refrigeration. A novel solid state elastocaloric refrigeration process using the large latent heats of shape memory alloys (SMA), specifically NiTi, could also hold potential in this field. This paper describes the development of a scientific test setup to investigate shape memory alloy based cooling processes. The setup allows for an independent control of the different variables, e.g. strain, strain rate etc., which influence the process functions. An integrated multi sensor system is used for synchronized measurement of mechanical and thermal quantities. First experiments demonstrate the control options of the test platform and the effect of each control variable on the elastocaloric cooling process.

Mise en place d'un test scientifique pour l'étude des processus de refroidissement élastocaloriques basés sur des alliages à mémoire de forme

Mots clés : Alliages à mémoire de forme ; Froid élastocalorique ; Refroidissement ; Claleur latente ; Changement de phase

* *Corresponding author*. Lab for Measurement Technology, Department of Mechatronics Engineering, Saarland University, Campus A 5.1, 66123 Saarbrücken, Germany. Tel.: +49 68130271347.

E-mail addresses: m.schmidt@lmt.uni-saarland.de (M. Schmidt), schuetze@lmt.uni-saarland.de (A. Schütze), stefan.seelecke@mmsl.uni-saarland.de (S. Seelecke).

[1] Tel.: +49 68130271341.

[2] Tel.: +49 6813024663.

http://dx.doi.org/10.1016/j.ijrefrig.2015.03.001

Nomenclature

T	temperature K
ΔT	temperature change K
L_0	length mm
ΔL	length change mm
ε	engineering strain $\Delta L\, L_0^{-1}$ (%)
F	Force N
A_0	cross section mm^2
σ	engineering stress $F\, A_0^{-1}$ (MPa)
ρ	density $g\, cm^{-3}$
c	specific heat capacity $J\, g^{-1}\, K^{-1}$

1. Introduction

The conventional compression refrigeration is used in many commercially available devices. The requirement for efficient and environmentally friendly cooling systems leads to the development of novel solid state refrigeration systems based on ferroic materials. These materials show different caloric effects, i.e. magnetocaloric, electrocaloric and elastocaloric (Fähler et al., 2012), with magnetocaloric refrigeration being the most established ferroic cooling technology today. After the discovery of the giant magnetocaloric effect (Pecharsky and Gschneidner, Jr., 1997) the number of developed magnetocaloric devices increased (Yu et al., 2010). An increasing interest for the use of electrocaloric materials for cooling devices could be observed after an adiabatic temperature change of 12 °C was obtained in PbZrTiO thin films (Mischenko et al., 2006). The investigations of Lu et al. (2010) show a significant electrocaloric effect in relaxor ferroelectrics, furthermore Jia and Sungtaek Ju (2012) and Chukka et al. (2013) developed solid-state cooling devices to study the electrocaloric cooling process. The elastocaloric effect of CuZnAl shape memory alloys (SMA's) has been investigated by Bonnot et al. (2008). Quarini and Prince (2004) showed the potential of NiTi-based SMA's for cooling applications. The usability of NiTi wires for potential cooling applications were demonstrated by Cui et al. (2012), in addition NiTi thin films have been studied by Ossmer et al. (2013). The comparison of different elastocaloric materials shows that NiTi-based materials provide latent heats of 22 $J\, g^{-1}$, which are considerable larger than the latent heats of CuZnAl (6.2 $J\, g^{-1}$) and CuAlNi (6.8 $J\, g^{-1}$) (Moya et al., 2014). The latent heats have a significant influence on the efficiency of a potential cooling process (Schmidt et al., 2013) and have to be taken into account when choosing the elastocaloric material.

In addition to the adaptation of the material properties to the specific requirements in terms of elastocaloric refrigeration (Bechtold et al., 2012) a comprehensive scientific test setup is needed to investigate the cooling process and optimize the process cycle. In the field of magnetic refrigeration, experimental devices have been developed to investigate the influence of the operating conditions on the process functions (work and heat) (Tušek et al., 2013), (Chukka et al., 2013). Similar setups have been designed for electrocaloric refrigeration (M. Ožbolt et al., 2014a), (Ožbolt et al., 2014b). The analysis of different elastocaloric materials with various sample dimensions requires a different type of experimental setup, which is capable of handling various samples. Furthermore, an independent control of the various process variables is required to study the effects of the operating conditions on the process functions.

2. Basics of an SMA based cooling process

For the determination of process relevant control variables a suitable SMA-based cooling process, following the Bryton cycle, is introduced (Fig. 1). This process is based on the elastocaloric effect during a stress induced adiabatic phase transformation from Austenite (A) to the tensile Martensite variant (M+). The temperature change during the phase transformation of pseudoelastic SMA's shows a strong rate-dependency of the applied mechanical field (Shaw and Kyriakides, 1995), (Chang et al., 2006).

The SMA-based solid state cooling process can be realized without any additional heat transfer medium. The elastocaloric material itself, in the shape of a ribbon, can function as a heat transfer medium. A heat source and a heat sink made out of metal blocks with a higher heat capacity than the SMA ribbon can be used to store thermal energy. Similar to the conventional vapor compression refrigeration cycle, the SMA-based cooling cycle can be divided in four phases, cf. Fig. 1.

1. Loading: The strain increase at a high strain rate leads to a near-adiabatic temperature increase of the SMA ribbon above the temperature of the heat sink. The large arrows in tensile direction indicate an increasing tensile stress.
2. Heat transfer to heat sink: At constant high strain the SMA ribbon contacts the heat sink. The heat sink absorbs heat from the SMA, the temperature of the SMA ribbon decreases and the temperature of the heat sink increases.
3. Unloading: The strain decrease at a high strain rate leads to a temperature decrease of the SMA ribbon below the temperature of the heat source. The small arrows indicate a decreasing tensile stress.
4. Heat transfer from heat source: At constant low strain the SMA ribbon contacts the heat source. The SMA absorbs heat from the heat source, the temperature of the SMA ribbon increases and the temperature of the heat source decreases.

This exemplary elastocaloric cooling cycle shows that, besides the aforementioned control variables, additional parameters have an influence on the process performance. The heat transfer between the elastocaloric material and the metal blocks is strongly influenced by the thermal conductivity of the materials, the contact force, the contact time and the surface of the contacting parts. Furthermore, the cycle time as well as the heat losses to the surrounding environment strongly influence the process efficiency. Finally, the process can be varied by bringing the elastocaloric material and the heat sink/source into contact before or during loading/unloading, i.e. changing the phase between applied strain and heat transfer.