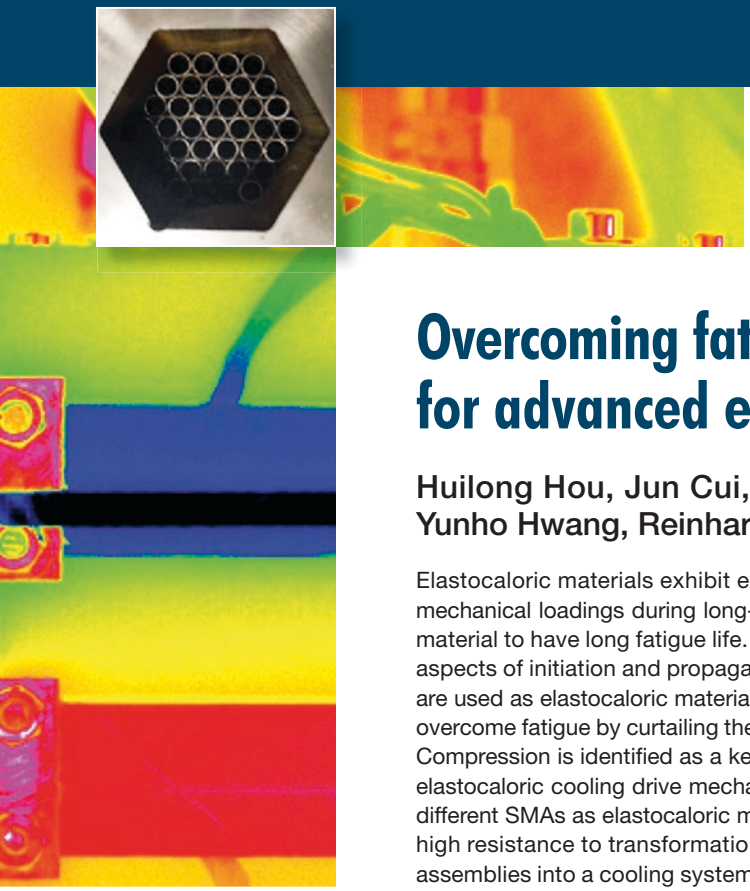


Overcoming fatigue through compression for advanced elastocaloric cooling

Huilong Hou, Jun Cui, Suxin Qian, David Catalini, Yunho Hwang, Reinhard Radermacher, and Ichiro Takeuchi

Elastocaloric materials exhibit extraordinary cooling potential, but the repetition of cyclic mechanical loadings during long-term operation of cooling systems requires the refrigerant material to have long fatigue life. This article reviews the fundamental cause of fatigue from aspects of initiation and propagation of fatigue cracks in shape-memory alloys (SMAs) that are used as elastocaloric materials, and highlights recent advances in using compression to overcome fatigue by curtailing the generation of surfaces associated with crack propagation. Compression is identified as a key means to extend fatigue lifetime in engineering design of elastocaloric cooling drive mechanisms. We summarize the state-of-the-art performance of different SMAs as elastocaloric materials and discuss the influence of low cyclic strains and high resistance to transformation. We present integration of compression-based material assemblies into a cooling system prototype and optimization of the system efficiency using work recovery and related measures.

Introduction

Solid-state cooling with caloric materials is a viable alternative to conventional vapor compression, and has the potential to take on a sizable share of the worldwide market in heating, ventilation, and air conditioning technologies.[1–3] Caloric materials are categorized as magnetocaloric, electrocaloric, or mechanocaloric when the cooling effect is driven by a magnetic, an electric, or a mechanical field, respectively. Mechanocaloric materials are further divided into elastocaloric materials, wherein uniaxial mechanical stress is used, and barocaloric materials, where isotropic stress such as hydrostatic pressure is applied to the material.[3,4] The first observation of the elastocaloric effect was probably on a piece of rubber dating back to 1859;[3] however, the systematic demonstration of elastocaloric cooling using shape-memory materials began only recently in 2012.[5,6]

The elastocaloric effect exhibits remarkable potential as manifested in the directly measured cooling ΔT of −17°C in Ni-Ti,[5] a level not easily achievable by other caloric materials. The exploration of elastocaloric materials has now been expanded from Ni–Ti-based alloys to Cu-based alloys and various magnetic alloys.[7] At the same time, elastocaloric cooling system prototypes have been demonstrated based on tensile,[8] compressive,[9] and bending modes.[10]

Elastocaloric cooling is based on shape-memory alloys (SMAs). An SMA is able to "remember" its original shape when heated above its martensitic transformation temperature.[11] SMAs in the austenite phase exhibit superelasticity where stress-induced phase transformation leads to a large reversible strain. Elastocaloric cooling takes place when the latent heat is absorbed back in the material during the reverse transformation from martensite to austenite in the unloading part of superelasticity.[5,7] Continuous operation of elastocaloric cooling requires repetitive application of stress to SMAs, and the large number of mechanical loading cycles can potentially lead to onset of fatigue. Fatigue causes deterioration of mechanical properties of a material and eventual failure under cyclic application of mechanical loads.[12]

In this article, we highlight recent efforts in overcoming fatigue associated with SMAs used in elastocaloric cooling, from fundamental mechanisms to the design of cooling devices and systems. The microstructural origins of fatigue

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and possible pathways to extend fatigue lives are reviewed from the perspective of solid mechanics. We describe tension-compression asymmetry unique to SMAs in terms of microstructural orientation dependence and macroscopic behavior. We explain the geometry and assembly of SMAs customized for compression-based elastocaloric devices and an accompanying heat-transfer subsystem. We address work recovery and related considerations for designing elastocaloric prototype systems. The directly measured cooling ΔT of various SMAs over cyclic loading is summarized.

Mechanisms of fatigue and relation to loading mode

The origin of fatigue is the initiation of cracks and their eventual propagation.[12,13] Compared to crack initiation, crack propagation can take place for a long period of time before eventual failure.[12] Slowing crack propagation is essential for maintaining the material's integrity over many cycles. **Figure 1**a illustrates the crack propagation after a large number of repetitive tensile stress cycles. The already initiated crack has a stress concentration around the tip of the crack. The stresses at the exact tip of a crack exhibit extremely large values and in theory approach infinity.[12] This is considerably higher than the yield strength of the material. A plastic zone arises in the vicinity of the crack tip with the ability to deform substantially, and the crack tip increases the radius of curvature in order to relax the stress concentration. Under tensile stress, new surfaces can be stretched out of the plastically deformed region with a blunt crack tip.[13] Upon removing the tensile stress, the newly generated surfaces require additional space to fold in, and thus they advance along the direction perpendicular to the axis of tensile stress. The advancing process repeats in the subsequent loading–unloading cycles.

On the other hand, compressive loading (Figure 1b) can delay the advancing of cracks by curtailing the driving force for generation of new surfaces. The extension of crack length can be slowed down in subsequent cycles. Furthermore, creating a thin, compressive layer on a material surface can improve fatigue strength up to 60%[14] and extend fatigue life nearly three times.[15] Therefore, compressive stress is an effective route to prolong the fatigue life of materials.

Mechanism of tension–compression asymmetry

Stress-induced martensitic transformation can be achieved through compressive or tensile stress. **Figure 2**a[16] shows the parameters in a single-crystal transformation from austenite (labeled "parent phase") to martensite. On the habit plane (an unrotated and undistorted plane), the maximum shear stress resolved from the external load can align positively or negatively with respect to the prescribed transformation direction.[17]

The shear component of the transformation direction can dominate over the normal component when there is only a slight volume change in single-crystal Ni-Ti.[18] The crystallographic constraints permit the martensitic transformation to initiate if the maximum resolved shear stress is positive toward the prescribed transformation shear direction.[17,19] As a result, the martensitic transformation exhibits a unidirectional nature at a crystallographic orientation for a given stress state, and has strong tension–compression asymmetry for a single crystal.[17]

When crystals are aggregated into textured polycrystals as commonly encountered in drawn wires or bars,[16,20] the tension–compression asymmetry due to the strong texturing is expected to be similar to the asymmetry resulting from

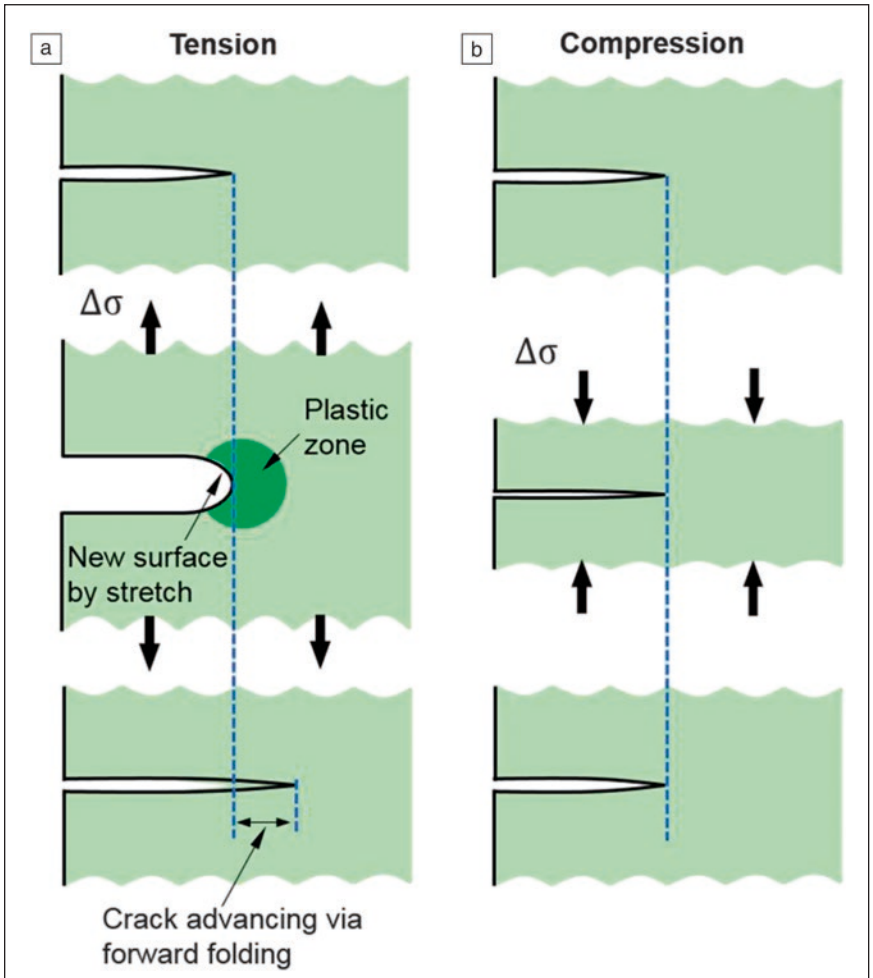


Figure 1. Mechanisms of crack propagation. Schematic of crack advancing under (a) tensile and (b) compressive cycles with stress amplitude Δσ. Adapted with permission from Reference 13. © 2007 Elsevier.

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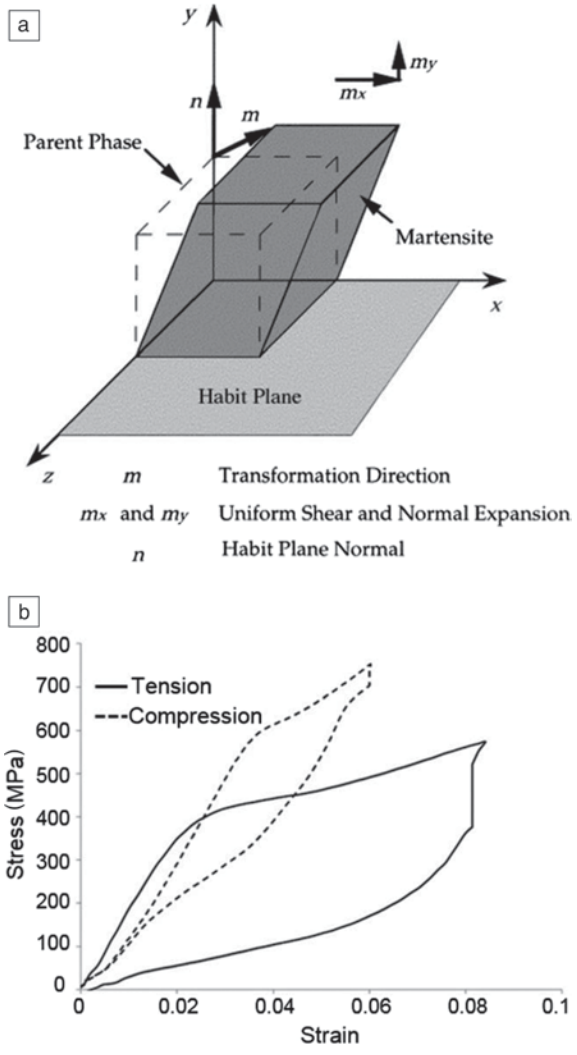


Figure 2. Tension–compression asymmetry in shape-memory alloys. (a) Schematic showing transformation parameters of favorably oriented martensite in stress-induced martensitic transformation. Reproduced with permission from Reference 16. © 1999 Elsevier. (b) Superelastic stress–strain curves obtained for polycrystalline Ni-Ti when applying tensile and compressive stress within the austenite state.[5]

crystallographic orientation dependence in single crystals. The compressive superelasticity of polycrystalline Ni-Ti wires in Figure 2b shows higher critical transformation stresses, greater transformation stress–strain slopes, and smaller transformation strains than those in tension. The difference is attributed to the dependence of the maximum resolved shear stress on crystallographic orientation and the stress direction.[16,17] For example, the [111] orientation in polycrystalline Ni-Ti has the maximum value of the orientation tensor (or Schmid factor[19]) of 0.39 for tension versus 0.27 for compression, while the [100] direction has values of 0.21 for tension versus 0.4 for compression. The larger the maximum value of the orientation tensor, the higher the effective conversion and thus the smaller the required applied stress.[16] Since the entire austenite domain is converted into martensite[21] and the cooling potential dictated by the latent heat (on the order of 10 J g^{-1} for Ni-Ti alloys[5,7]) is fully unleashed, compression can deliver the same cooling capacity as tension and extend the fatigue life despite the necessary high transformation stress and the large transformation stress–strain slope.

Compression-based design of elastocaloric materials

The understanding of the benefits of compression motivates the utilization in designing cooling devices with SMAs as the solid refrigerant.[9,22] SMA tubes have been chosen as refrigerant components to allow the cooling medium (typically water) to flow through. **Figure 3**a[22] shows one example configuration of the SMA tubes in a bundle. To prevent buckling (a common failure mode under compression), the tubes are grouped into a hexagonal cross-sectional shape preserving symmetrically distributed stress, and a rigid holder is employed for lateral mechanical support (Figure 3b[23]). After cooling is generated in the bundle of SMA tubes, heat-transfer fluid carries the heat. Additional components to compress tubes with fluid flowing are illustrated in Figure 3c. Figure 3d shows the completed Ni-Ti tube bundles supported by linear bearings to ensure axially compressive loading. A cooling capacity of 100 W can be generated in one bundle with twenty 250-mm-long Ni-Ti tubes with outer diameter of 4.7 mm, inner diameter of 3.8 mm, and latent heat of 12 J g^{-1} operated at 0.1 Hz.[9] The cooling power scales proportionally with the total material mass and with the operation frequency.[22]

Designing compression-based elastocaloric systems

Full recovery of strain in SMAs upon unloading is shown in **Figure 4**a. A mechanical system can be devised so that unloading force in one material can be harnessed as a part of the driving stress for another material. The configuration in Figure 4b is realized by axially aligning two SMA tube bundles. Each bundle is initially in a compressed state with half of the maximum reversible strain. When bundle 1 is compressed by means of an input actuation mechanism applied via the movable frame, the unloading force from half strain to zero strain of bundle 2 assists in driving the movable frame so that the required input work for bundle 1 is reduced. This process is called work recovery. When bundle 1 is loaded to reject heat, bundle 2 is unloaded to absorb heat and deliver cooling, which repeats in a reciprocating manner. Figure 4c depicts experimental stress–strain curves for the two SMA bundles during one cycle of operation of the prototype. When strain is increased in bundle 1, strain is decreased in bundle 2 in a synchronized manner. A process of heat recovery can also be implemented to improve the heat-exchange efficiency of the entire system.[24] Optimization of the system configuration with work recovery and heat recovery enhanced the coefficient of performance

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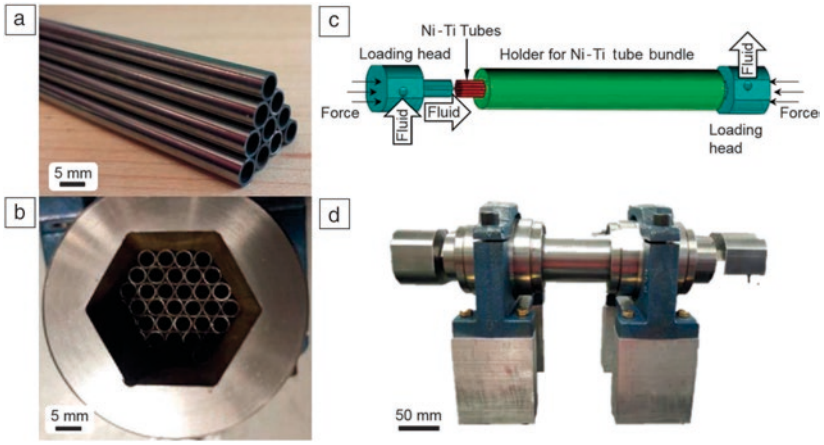


Figure 3. Compression-based design of Ni-Ti materials for elastocaloric systems. (a) Geometry of Ni-Ti tubes and a stack of multiple tubes and (b) assembly of a bundle of Ni-Ti tubes into a holder to prevent buckling.[22,23] (c) Schematic of Ni-Ti bundles and loading heads. The heat exchange fluid is made to flow through the tubes for heat transfer.[9] (d) Picture of final assembly of the loading heads and Ni-Ti bundles in a linearly aligned configuration for an elastocaloric system.[22]

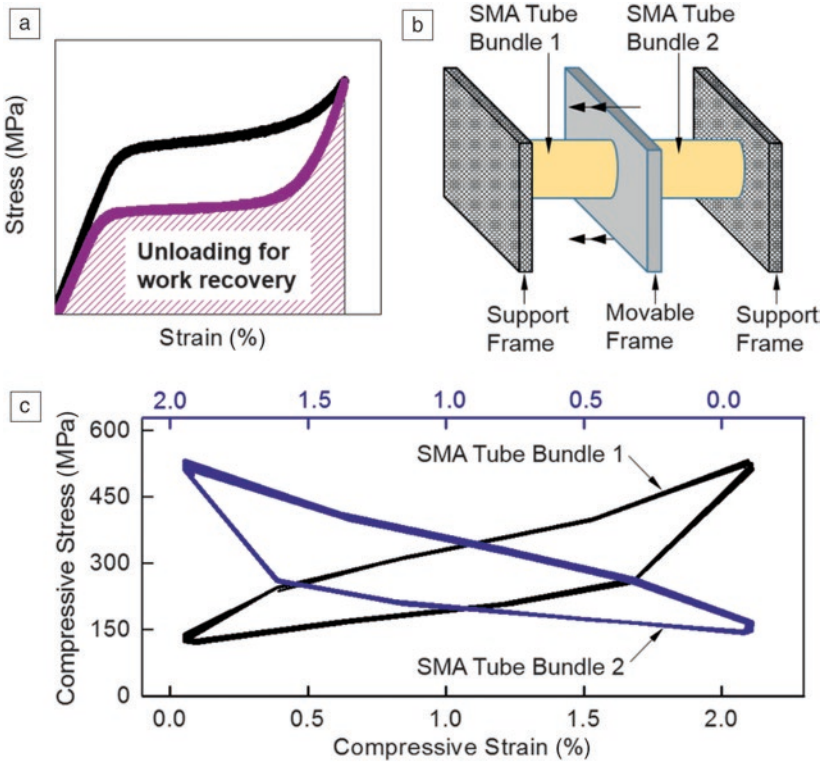


Figure 4. Concept of work recovery, and the implemented work-recovery design in an elastocaloric system. (a) Schematic of the typical superelastic behavior in shape-memory alloys (SMAs).[7] (b) Concept of work recovery achieved by linearly stacking two SMA tube bundles.[9] The double arrows above the movable frame signify the axis of movement. (c) Compressive stress–strain curves of the two SMA tube bundles in a prototype system to incorporate work recovery. The bottom *x*-axis has increasing values and the top *x*-axis has decreasing values.

by 30% to 4.1 compared to SMAs produced without work and heat recovery processes.[9]

Compressive stability of elastocaloric cooling

Extending fatigue life of materials may also be achieved by implementing mechanically robust SMA materials and by applying smaller strains.[13,25] The endurance limit—a stress amplitude below which failure is avoided—has a positive correlation with the ultimate strength.[13] **Figure 5**[26–31] shows a summary of elastocaloric materials and their performance indicating that high-strength materials such as Ni-Ti with transformation stress of ≈650 MPa (versus ≈150 MPa in Cu-Zn-Al) can produce stable elastocaloric cooling over 10,000 cycles under compression without degradation. High-strength materials can thus have long fatigue life and the potential for stable elastocaloric cooling. If one envisions a 10-year operation of a commercial elastocaloric cooling device such as an elastocaloric air conditioner, this would require about a million cycles of SMAs under 0.05 Hz operation, assuming usage for half a day for six months in a year. The fatigue requirement of SMAs would further become less stringent if there is lower frequency of device. Decreasing applied strain can lead to extended fatigue life,[25,32] and from Figure 5, a small amplitude of strain such as 1.0% in Fe–Pd (versus 6.0% in Cu-Zn-Al) appears to help maintain elastocaloric cooling cycles despite concomitantly reduced cooling ΔT. As previously discussed, cyclic tension can lead to fracturing in a relatively smaller number of cycles, as marked by the X for Ni–Ti in Figure 5.

Concluding remarks

Compression-based elastocaloric cooling enables extended operation due to prolonged fatigue lifetime in SMAs compared to tension-based cooling. This is due to the unidirectional nature of stress-induced martensitic transformation and the tension–compression asymmetry in superelasticity inherent to SMAs. Employing mechanically strong alloys and applying low strains are also good strategies to facilitate long-term operation of elastocaloric cooling materials. Compression-based elastocaloric cooling has been successfully implemented in the development of elastocaloric prototype systems. Based on compression-based designs, exploration of high-capacity elastocaloric materials for extended cooling and

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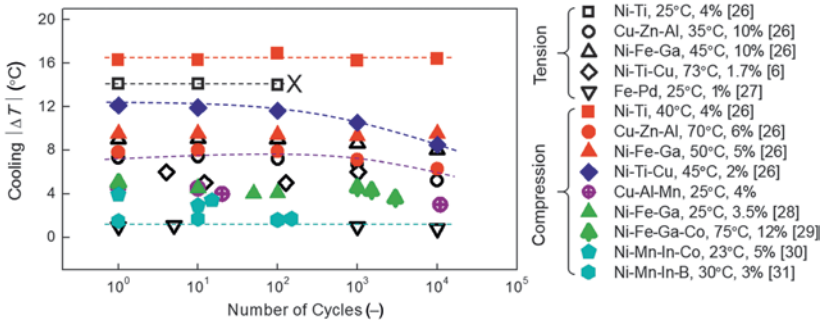


Figure 5. Evolution of elastocaloric cooling performance of different materials over cycles of operation. Absolute value of cooling ΔT versus cycles in different classes of shape-memory alloys. Unfilled symbols are for tensile mode, and solid symbols are for compressive mode. A crossmark indicates the cycle where failure took place, while no crossmark means there was no failure at the end of cycling. The test temperature, T_{test}, and the strain amplitude, $\Delta\varepsilon$, of each material are displayed in the legend.[6,26–31]

optimization of systems with improved heat transfer can competitively advance elastocaloric cooling into the arena of practical cooling technologies.

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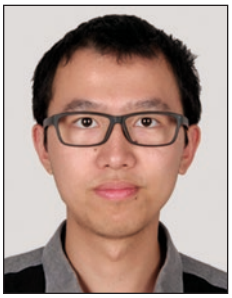
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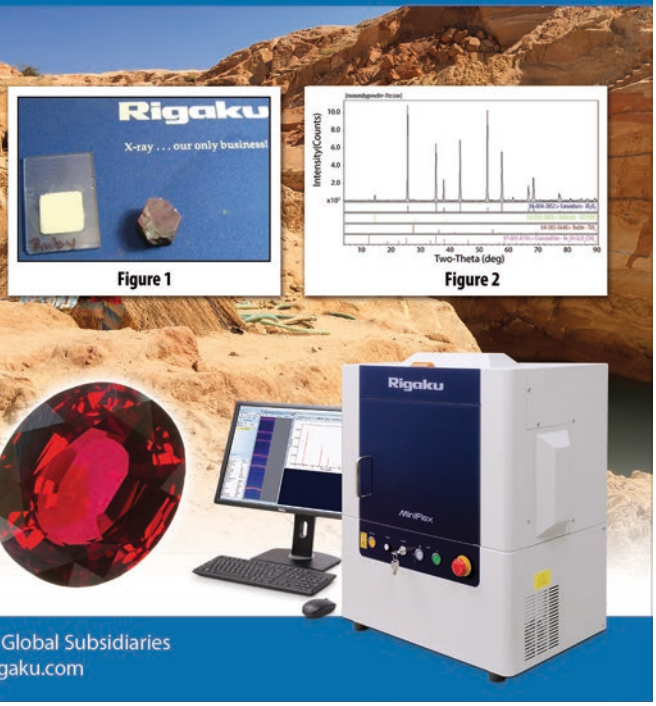
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This gem would be more appropriately called a red sapphire.



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