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TEST FACILITY FOR SCREENING AND EVALUATING CANDIDATE MATERIALS FOR ADVANCED MICROTURBINE RECUPERATORS

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ABSTRACT

A test facility for screening and evaluating candidate materials for advanced microturbine recuperators is described. The central piece of the test facility is a modified 60 kW Capstone microturbine that serves as a test bed for subjecting test specimens to conditions of stress, environment and temperature that are representative of those experienced by the recuperator during microturbine operation. Special provisions have been incorporated into the design of this test facility for controlling the magnitude of the applied mechanical stress and the surface temperature of the test specimens with the objective of carrying out accelerated testing. Candidate materials for evaluation in this test facility are identified.

INTRODUCTION

The challenging performance targets for the next generation of microturbines include fuel-to-electricity efficiencies in the 40-45% range, capital costs less than $500/kW, NOx emissions reduced to single parts per million, several years of operation between overhauls, and fuel flexibility [1]. It is clear that significant increases in microturbine efficiency can only be achieved with increases in engine operating temperatures, but because most of the current microturbine designs utilize metallic components without air-cooling, higher operating temperatures without any improvements in materials performance would result in shortened lifetimes. Therefore improvements in microturbine efficiency can only be realized through the use of advanced metallic alloys and ceramics for high-temperature components, thus making advanced materials a key enabling technology for achieving the performance targets of the next generation of microturbines.

One of the critical components in low-compression ratio microturbines is the recuperator, which is responsible for a significant fraction of the overall efficiency of the microturbine [2]. Conventional recuperators are thin-sheet metallic heat exchangers that recover some of the waste heat from the exhaust stream and transfer it to the incoming air stream. The preheated incoming air is then used for combustion because less fuel is required to raise its temperature to the required level at the turbine inlet. The most effective conventional compact metallic recuperators can produce 30-40% fuel savings from preheating [2]. Most of today's compact recuperators are manufactured using 300 series stainless steels which are used at exhaust-gas temperatures below about 675° C [3]. At higher temperatures, these materials are susceptible to creep deformation and oxidation which lead to structural deterioration and leaks, reducing the effectiveness and life of the recuperator. As engine operating temperatures will increase to improve overall efficiency, advanced metallic (or even ceramic) recuperators will be necessary [3]. However, developmental efforts will be needed to adapt current recuperator manufacturing processes to advanced alloys, to reduce costs, and enable long-term reliable operation at higher temperatures.

A number of candidate materials for the next generation of microturbine recuperators have been identified based on their resistance to creep deformation in air [4], and on their resistance to corrosion in air and simulated exhaust gas environments [5]. Experimental methods at the bench-scale (e.g.- isothermal creep tests in air, or isothermal thermogravimetric measurements in controlled environments) are ideal and desirable to study the effects of stress, temperature and environment on the properties, durability and reliability of materials in a manner that is scientifically and technologically tractable. However, bench scale testing does not reproduce the complex conditions to which microturbine components (e.g.- recuperator) are subjected during operation. Understanding the complex relationships and interactions among stress, temperature, environment and manufacturing operations, and their effect on the durability and reliability of materials is an issue of both scientific and technological relevance. To date, there is little or no such data.

The relatively low-cost of acquisition and operation of microturbines makes them an ideal test platform for screening and evaluating materials and components in controlled field tests. As part of a program sponsored by the US Department of Energy to support microturbine manufacturers in the development of the next generation of microturbines, a task has been established at Oak Ridge National Laboratory (ORNL) with the objective of screening and evaluating candidate materials for advanced microturbine recuperators. As part of this task, ORNL has acquired a new 60 kW Capstone microturbine to be used as a test platform for materials screening and evaluation. In collaboration with Capstone Turbines, Corp., this microturbine has been specially modified to achieve recuperator inlet gas temperatures as high as 850°C.

The methodology for screening and evaluating candidate materials for microturbine recuperators will consist in fabricating special test specimens, and then subjecting them to mechanical stresses while exposed to the microturbine exhaust gases in a location upstream from the recuperator. The evolution of the candidate materials microstructures, and their physical and mechanical properties, will be quantified as a function of time and history of exposure using an array of characterization techniques that include analytical electron microscopy, infrared imaging, and conventional mechanical testing of miniature tensile specimens and micro and nanoindentation.

One advantage of the approach proposed in this methodology is that the preparation of test specimens will enable the identification of potential manufacturing and/or welding barriers. Furthermore, this approach will also permit assessing the effect of cold work and large-scale plastic deformation, which occur during the primary surface recuperator manufacturing process, on the resistance of the material to oxidation and creep deformation.

The modified 60 kW microturbine will be operated under various modes to investigate the durability and reliability of candidate materials when subjected to intermittent (peak shaving mode) or steady state (base load mode) conditions. Furthermore, tests campaigns will be designed for accelerated materials testing.

EXPERIMENTAL

Microturbine

The central piece of the test facility is a modified 60 kW Capstone microturbine electric generator system shown schematically in Figure 1. This system incorporates a compressor, a recuperator, a combustor, a turbine and a permanent-magnet generator. The rotating components are mounted on a single shaft supported by air bearings that rotate at up to 96,000 rpm. The fuel system includes a gas compressor that operates with a minimum inlet pressure of 0.5 psig and provides a maximum outlet pressure of 100 psig. The microturbine was connected to the local electric grid, and a wattmeter quantifies the amount of electric power produced.

Figure 2 shows a schematic of the microturbine generator system and illustrates the location of the annular recuperator with respect to other engine components. Figures 3 and 4 are photographs of a recuperator and of an individual air cell, respectively. The recuperator is about 45.7 cm in diameter, and is comprised of 169 air cells. Each air cell is fabricated by welding individual fin-folded 347 stainless steel sheets that were 100 µm in initial thickness.

The control system of the microturbine was modified to allow for higher temperatures of operation and various operating speeds, but the speed was limited to 60,000 rpm to avoid compressor surge conditions present at higher speeds with increased temperature operation. At 45,000 rpm for example, the maximum recuperator gas inlet temperature is 843°C. To allow the insertion of test specimens upstream from the microturbine recuperator, six different sample holder bosses were welded around the pressure vessel that encloses the turbine. These sample holder bosses vary in diameter from 24 to 90 mm and Figures 5a. and 5b show photographs of their relative location.

Test Specimens

Test specimens will be prepared following standard methods that are employed for the manufacture and fabrication of primary surface recuperators. Figure 6 shows a schematic of the sequence of operations that will be followed to prepare test specimens. Foil material of thicknesses ranging between 75 and 250 µm will be evaluated. To investigate the effect of cold plastic strain on the durability of the material and its resistance to corrosion and creep deformation, some test specimens will be stamped using a die and a servohydraulic mechanical testing machine. Cold plastic strain is introduced when the foil material is folded into a corrugated pattern. The behavior of these specimens will be compared to that of test specimens fabricated from flat unfolded foils, but in both cases, the test specimens will be welded or brazed, to obtain a closed cylindrical shape.

During normal microturbine operation, the air cells of primary surface recuperators experience thermally and mechanically-induced stresses. These loads arise from pressure and temperature differences across the foil thickness, and temperature gradients in the air cell, that results from the counterflow of cold compressed air and hot exhaust gases [2]. At high homologous temperatures these mechanical stresses can induce excessive creep deformation of the recuperator material after long times, leading to the closure of the flow channels in the air cells. To quantify the creep resistance of candidate materials and investigate the effect of mechanical stress on their durability and reliability, test specimens will be mechanically stressed during the exposure tests inside the microturbine. This will be accomplished by subjecting the test specimens to internal pressurization using the specimen holder shown schematically in Figure 7 and compressed air. When necessary, test specimens will be constrained radially using rings to prevent excessive ballooning that may occur as a result of internal pressurization. In various cylindrical primary surface recuperator designs, ballooning of the recuperator air cells is prevented by welding the walls of the air cells, at many locations during each turn.

Accelerated Testing.

One of the objectives of the US DOE Advanced Microturbines Program is to develop improved microturbine systems capable of reliable service operation at higher temperatures for periods of time measured in tens of thousands of hours. To support this objective, this task, in coordination with another task in the program, is focused on collaborating with manufacturers of microturbine recuperators to identify and select materials for microturbine recuperators capable of meeting these service life requirements. Traditional life data analysis involves the simple analysis of time-to-failure data obtained under normal operating conditions. In the case of microturbine recuperators, however, such life data (or time-to-failure data) could be very difficult to obtain because of the long-life service times involved. Given this limitation and the need to observe failures of candidate materials to better understand their failure modes, special methods will need to be employed to force test specimens to fail more quickly than they would under normal use conditions.

Accelerated life testing involves acceleration of failures with the purpose of quantifying the life characteristics of materials and components at normal use conditions. Accelerated life testing can be qualitative or quantitative. In qualitative accelerated testing, the focus is set on identifying failures and failure modes without attempting to make any predictions as to the component's life under normal use conditions. In quantitative accelerated life testing, the objective is predicting the life of the material or component at normal use conditions, from data obtained in an accelerated life test [6].

Qualitative tests are used primarily to reveal probable failure modes. However, if not designed properly, these tests may cause the component to fail due to modes that would have never been encountered in real life. A good qualitative test is one that quickly reveals those failure modes that will occur during the life of a component under normal use conditions. In general, qualitative tests do not quantify the life (or reliability) characteristics of the component under normal use conditions. However, they do provide valuable information as to the types and level of loads one may wish to employ during a subsequent quantitative test. Quantitative accelerated life testing, unlike the qualitative testing methods, consists of testing designed to quantify the life characteristics of the component or system under normal use conditions, and thereby provide reliability information [6].

Test campaigns that include accelerated testing will be designed to screen and evaluate candidate materials for advanced microturbine recuperators under two general conditions of microturbine operation: continuous (base load) and intermittent or cycling (peak shaving). Accordingly, acceleration test methods will be implemented to obtain time-to-failure data at an accelerated pace. These test methods will be based on the application of loads (e.g.- temperature, stress) which exceed those that recuperators would experience under normal use conditions, and will use the times-to-failure data obtained in this manner to extrapolate to use conditions. It will be critically important to carefully choose thermal and mechanical load levels that accelerate the failure modes under consideration, but do not introduce failure modes that would never occur under normal operating conditions. The magnitude of these loads and overloads will be determined by collaboration with manufacturers of microturbines and microturbine recuperators, based on design considerations, on knowledge acquired from the analysis of results of creep and oxidation tests, and microstructural characterization of those specimens. Mechanical overstressing will be achieved by controlling the magnitude of the compressed air pressure used to mechanically-stress the test specimens. Thermal overloading, beyond the temperature provided by the microturbine exhaust gas stream, will be accomplished through the use of resistance-heated heating elements positioned next to the test specimens. The surface temperature of the test specimens will be monitored using thermocouples and infrared imaging when practical. In all cases, these tests will be followed by thorough characterization of the material.

Post-test characterization of test specimens will include evaluation of mechanical properties by testing miniature tensile specimens and by indentation tests using a mechanical property microprobe (nanoindenter) equipped with a spherical probe. The value of Young's modulus, hardness, and fracture toughness of the base metal and its corrosion products will be determined, as well as the adhesion strength between the base metal and these corrosion products.

The chemical composition of the material and its corrosion products will be determined by electron microprobe analysis and analytical electron microscopy. Of particular interest will be the determination of the concentration and spatial distribution of elements that are responsible for the formation of protective coatings on the surface of the recuperator materials (e.g.- aluminum or chromium), and sub-scale/metal interfacial structure.

Because the effectiveness of recuperators is heavily dependent on the material's thermal transport properties, the thermal conductivity of the materials under investigation will be determined at various stages, starting with fabrication and at various intervals during the exposure tests. It is likely that the thermal conductivity of the material will change as a result of oxidation, corrosion or deformation, and that the magnitude of these changes will vary with the thickness of the oxidation/corrosion product's layer, and aging effects in the metallic foils. Knowing how the physical and mechanical properties of these materials evolve with time during service will be important for the formulation of life prediction models. Furthermore, the evolution of the thermal properties is of particular interest because measurements of thermal conductivity have the potential of being a powerful non-destructive evaluation tool to monitor and keep track of residual properties of microturbine recuperator materials.

It is expected that the evolution of the oxide products, their properties and their resistance to spallation will be most critical during intermittent microturbine operation. During intermittent operation the recuperator will be subjected to large strains during heating/cooling that may lead to spallation of the protective oxide layer, and result in exposure of the base material to oxidation/corrosion. Therefore, special attention will be given to the design of test campaigns to evaluate the behavior of candidate recuperator materials under these aggressive conditions. Considering the differences in the thermal and mechanical loading conditions that microturbine recuperators experience during continuous or intermittent operation, it is likely that the experiments to be carried out in the test facility described here will lead to the selection of materials that are best suited for one, the other, or both modes of operation.

The first sample holders (see Figure 7) and test specimens had been fabricated using the same material to avoid undesirable mechanical stresses that may arise from differences in thermal expansion behavior. The materials that will be evaluated have been selected in collaboration with various manufacturers of microturbines and microturbine recuperators, based on the results and analysis of previous isothermal creep and thermogravimetric tests.

Candidate Materials.

Primary surface recuperators are typically fabricated from thin (75-150 µm) metal foils, such as type 347 stainless steel, which are then folded (die stamped) into a corrugated pattern. These corrugated foils are then welded in pairs to form air cells. The increase in recuperator gas inlet temperature that will accompany increases in microturbine efficiency will require the use of stronger, and in some cases less ductile, alloys. This is relevant because the ability to fabricate some types of recuperators will depend on whether the metal can be rolled into thin foils and then folded into a corrugated pattern [6].

Recuperator materials requirements are defined by a specific microturbine configuration and by the complex relationships between thermal efficiency, turbine rotor inlet temperature, recuperator hot-gas inlet temperature, compression ratio, and recuperator efficiency [2, 3]. For a single-shaft engine with radial flow, low power range of 25 to 75 kW, and a compression ratio less than 6, the following temperature use limits have been identified based on the magnitude of the material tensile strength and its resistance to corrosion, oxidation, and creep deformation [2-5]:

Table 1.

alloy	Maximum Temperature
400 series ferritic alloys	600°C
300 series austenitic alloys	650°C
advanced austenitic alloys	750°C
Nickel-based superalloys	800-850°C
NiCrAl or ODS FeCrAl alloy	900°C

The corrosion resistance of type 347 stainless steel is due to its 12-18% chromium (Cr) content, which forms a protective, adherent chromium oxide film on the surface of the alloy. Ideally, the formation of a dense adherent external oxide layer inhibits transport of oxygen to the material below the film, thus protecting the alloy from excessive additional oxidation damage. However, in the presence of water vapor this and other alloys that rely on the formation of Cr_2O_3 for oxidation protection (e.g.- SS 310, 20/25/Nb, 253MA, and Haynes 230) can experience accelerated attack due to the evaporation of Cr_2O_3 as $CrO_2(OH)_2$, and the loss of the protective surface layer contributes to accelerated attack. Higher Cr contents appear to eliminate the accelerated attack, but the volatilization of Cr_2O_3 still results in additional Cr depletion. At higher temperatures, this protective layer grows at a faster rate, which can lead to oxide spallation and Cr depletion. This can limit the performance life of these materials because the decrease in the effective cross section can lead to failure due to creep deformation. Alumina-forming alloys (e.g.- Haynes 214, and NiCrAl and ODS FeCrAl alloy PM2000) are attractive for this application because Al_2O_3 is not susceptible to water vapor-accelerated evaporation and is slower growing than Cr_2O_3 [5].

Initial screening and evaluation tests will be carried out with the following materials: HR120, Haynes 214, Haynes 230, 625 LCF, Alloy 864, Haynes 120, modified 803 and modified stainless steels.

SUMMARY

A test facility has been designed for screening and evaluating candidate materials for advanced microturbine recuperators. The central piece of the test facility is a Capstone 60 kW microturbine that has been modified to operate at recuperator gas inlet temperatures as high as 843°C and to allow for the exposure of test specimens at locations upstream from the recuperator. Special test specimen geometries along with a test methodology have been developed to investigate the effects of stress, temperature and various manufacturing operations, in particular folding and welding, on the resistance of the materials to creep deformation and corrosion/oxidation. Provisions for carrying out accelerated tests through thermal and mechanical overloading have been incorporated in the design of the test facility. Initial tests in this test facility have been scheduled to evaluate the following alloys: HR120, Haynes 214, Haynes 230, 625 LCF, Alloy 864, Haynes 120, modified 803 and modified stainless steels.

ACKNOWLEDGMENTS

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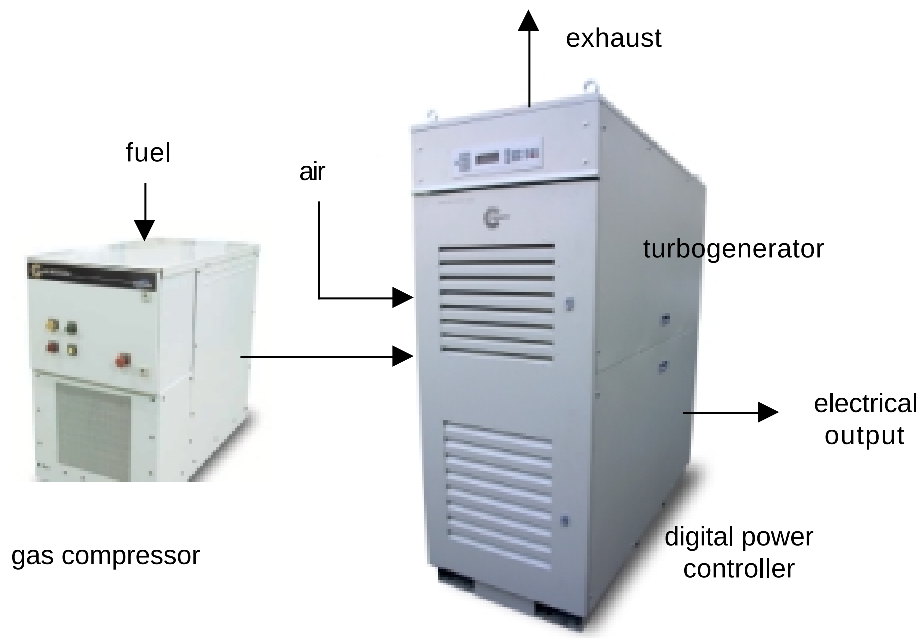

Figure 1. Microturbine System.

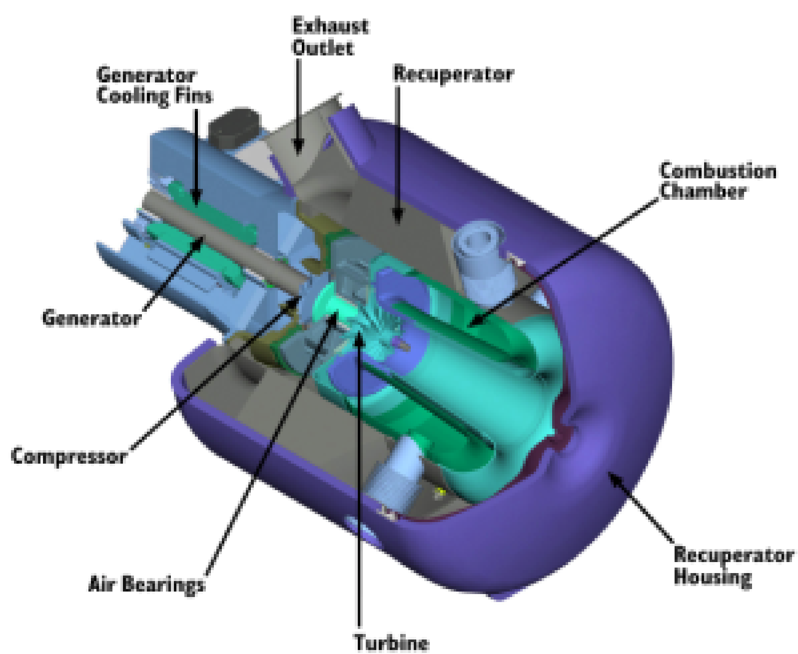

Figure 2. Schematic of turbogenerator system listing principal components

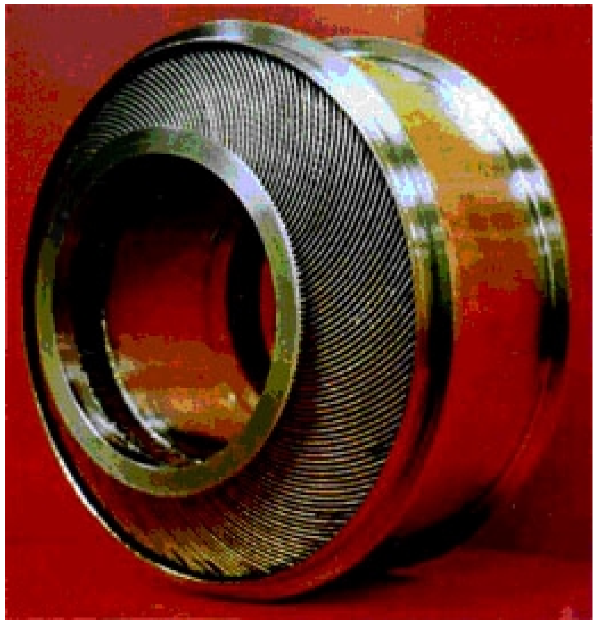

Figure 3. Stainless steel radial recuperator

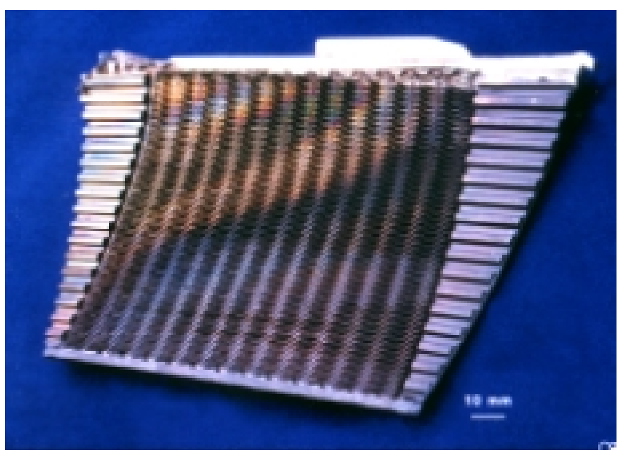

Figure 4. Air cell

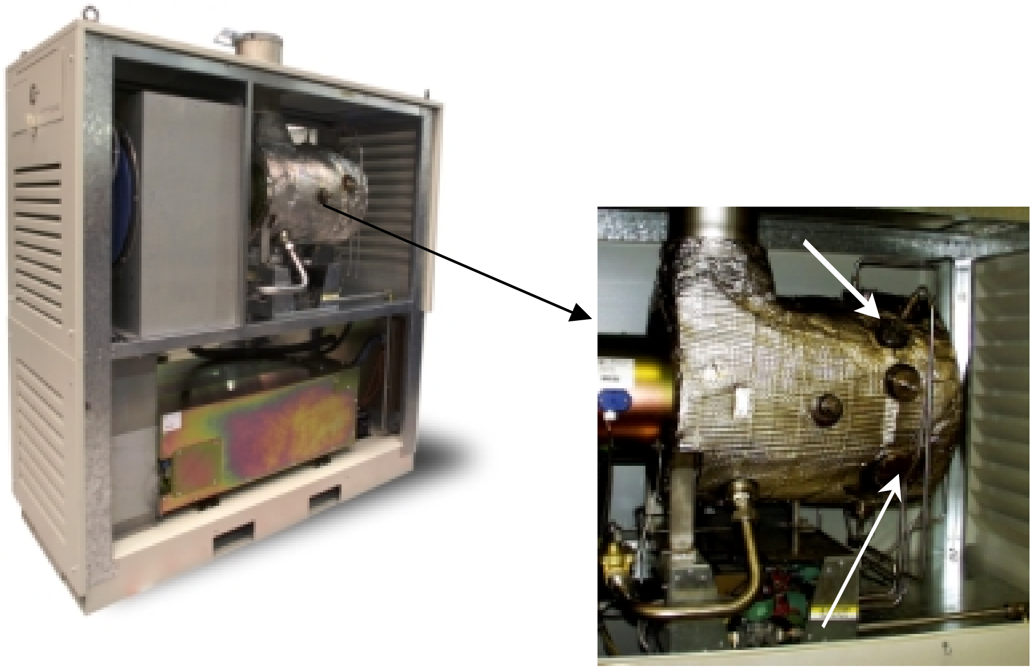

Figure 5. a) ORNL' 60 kW Capstone microturbine with cover removed. b) Location of two ports for sample holder insertion are indicated with arrows.

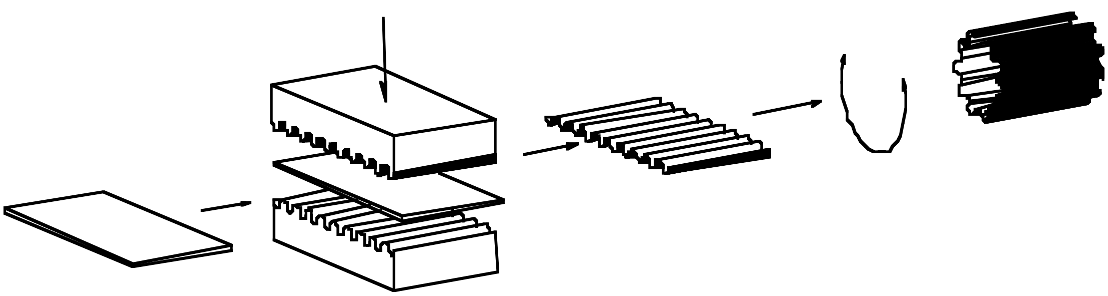

Figure 6. Schematic of process for fabrication of test specimens. It involves cold stamping to introduce corrugations on foil material followed by welding to obtained a closed cylindrical geometry.

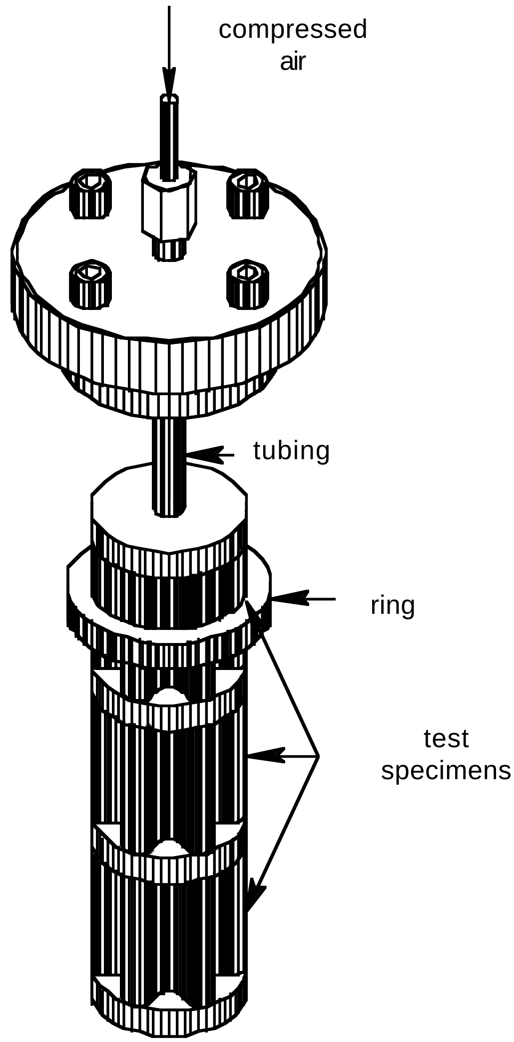

Figure 7. Schematic of sample holder. It shows corrugated test specimens welded to sample holder. Test specimens are mechanically-stressed using compressed air.