607f Analysis of Ductile and Brittle Failures from Creep Rupture Testing of Hdpe Pipes

Raj K. Krishnaswamy

High-density polyethylene (HDPE) pipes are used extensively for the transportation and distribution of natural gas, with over 80% of the new piping installations using HDPE. One striking example that highlights the strength of HDPE pipes can be found in the aftermath investigations of the Kobe (Japan) earthquake of 1995 during which the many fires and explosions from damaged gas pipelines caused considerable damage to life and property. However, there are no indications of HDPE pipe failure even under this extreme service condition. It was reported that the steel pipes failed and caused the aforementioned damage.

HDPE pipes used for gas transport are under pressure for the duration of their useful service. Often, fluctuations in pressure render the load to be dynamic. Therefore, it is important to establish the maximum load that such a pipe can withstand without deformation and damage over its' expected lifetime (typically, many decades). It is highly impractical to predict the durability and the design stress of pipes using short-term tests such as the tensile or flexural tests. The design stress and the useful service lifetime of HDPE pipes are therefore estimated by performing creep rupture tests at multiple temperatures. In this test, the pipe of interest is subjected to a certain hydrostatic pressure (expressed as hoop stress) and the failure time is recorded; failure is defined as a continuous loss of pressure within the pipe. Typically, a log-log plot of pipe hoop stress versus failure time is constructed and extrapolated to a desired lifetime. The corresponding hoop stress at the desired lifetime and temperature from the above-mentioned plot is used as the design stress (after the application of an appropriate safety factor) for the application of interest.

While HDPE has been successfully employed in pressure pipe applications for many decades now, a clear understanding of the relationships between molecular architecture and hydrostatic pressure performance is yet to emerge. In this investigation, a very wide spectrum of HDPEs were chosen such that they differed considerably in their architectural and compositional make-up. These polymers were converted into pipe (constant dimensions) under fairly similar extrusion processing conditions. These pipes were subjected to extensive creep rupture testing (hydrostatic pressure testing) at multiple hoop stress levels and temperatures. Comprehensive analysis of the pipe creep rupture data indicates that the ductile failure of such pipes is primarily driven by the yield stress of the polymer. In other words, in creep rupture testing, the failure time is dependent only on the applied hoop stress and the yield stress of the polymer (or pipe) as long as the failure mode is ductile. At a given hoop stress and test temperature, the failure time for ductile fracture was observed to depend exponentially on the tensile yield stress of the polymer or the pipe. This means that the primary material property that contributes to the ductile failure of HDPE pipes is density or crystallinity; consequently, the ductile failure of HDPE pipes is independent of molecular weight, molecular weight distribution and branching (short and long) distribution.

Analysis of pipe creep rupture data at multiple temperatures indicates that a simple time-temperature superposition is not strictly applicable to predict the design stress and durability of pressure pipes. Normalization of ductile failure data at multiple temperatures indicates a systematic improvement in performance with increasing temperature in the range between 20 °C and 80 °C. Thermal characterization of the as-made and annealed (80 °C) pipes indicates marginal (less than two weight percent) increase in crystallinity. While this small increase in crystallinity will contribute to longer failure times in the ductile failure mode, the level of performance improvement observed while testing at higher temperatures is considerably greater than can be accounted for by a change in crystallinity. Therefore, we propose that testing at higher (above-ambient) temperatures causes the residual stresses in the pipe to relax to some extent. This causes the pipe to perform better as residual stresses are known to help accelerate the fracture process. Consequently, one has to be careful about drawing conclusions from tests performed on compression molded specimens that are devoid of the microstructure and residual stresses that are typical of extruded pipes.

It is widely recognized that brittle fracture (through the initiation and subsequent crack propagation mechanism) at low stresses is the most common mode of failure for pressure pipes. Consequently, there has been considerable effort devoted to the duplication of such a fracture process in accelerated lab-scale tests. The development of PENT (ASTM F1473) is one outcome of such an endeavor. In our analysis of pipe creep rupture fracture, we find no correlation, whatsoever, between brittle failures in pressurized pipes and the PENT failure times. Therefore, one has to be extremely cautious in interpreting the true value of the PENT test when developing polymers and pipes for high-performance pressure pipe (PE100 & PE100+) applications.