The cyclic deformation and damage behaviors of AlSi piston alloys are comprehensively studied. A hysteresis energy-based LCF life prediction model was developed and utilized. Based on the model, the optimum fatigue life was found at intermediate temperature, which is derived from microstructure damage behavior. It is found that both of the fatigue cracking resistance (fatigue damage exponent *β*) and the crack propagation resistance(intrinsic fatigue toughness *W*0) dominate the LCF damage mechanism evolution with temperature increasing. An optimization strategy for LCF property optimization was proposed and verified by the experimental results of two typical AlSi alloys at different temperatures. As a result, increasing *W*0 at low temperature and increasing *β* at high temperature could be an effective way to enhance the fatigue life in entire service temperatures. In this way, the remarkable improvement of the LCF properties can be achieved with ultrasonic melt treatment.