APPLICATION OF RAPID INFRARED HEATING TO ALUMINUM FORGINGS

Puja B. Kadolkar[1]; Hui Lu[2]; Craig A. Blue[1]; Teiichi Ando[2]; Rob Mayer[3]
[1]Oak Ridge National Laboratory, Metals & Ceram. Div., 1 Bethel Valley Rd., Oak Ridge, TN 37831 USA
[2]Northeastern University, Mech., Industrial & Mfg. Engg., 360 Huntington Ave., Boston, MA 02115 USA
[3]The Queen City Forging Company, 235-B Tennyson St., Cincinnati, OH 45226 USA

ABSTRACT

Energy savings and enhancement of mechanical properties in aluminum forgings, produced in 2000 series alloys, processed by rapid infrared (RI) radiant heating were investigated. Pilot-scale production with a hybrid infrared system indicates 50-90% energy savings relative to conventional production with convective furnace heating with a significant decrease in process cycle times. Rapid preheating prior to forging produced finer grain sizes in solutionized specimens than those in specimens preheated in a gas-fired convection furnace. The reduced grain size gives the forgings longer fatigue life when tested in the solutionized and aged condition. Specimens forged with RI-preheating showed stronger age hardening, verified by hardness and tensile tests, than those forged with conventional furnace preheating. RI processing potentially leads to energy-efficient, low cost commercial production with improved mechanical properties.

INTRODUCTION

Increasing demand for energy efficiency, cost reduction and international competitiveness are some of the challenges US forging industries have been traditionally facing. Even today, the rapid increase in the energy prices and the growing energy consciousness continue to force industrialist to integrate their forging process with newer, improved and cost-efficient techniques. Amongst the several procedures involved in a forging operation, preheating of the metal billets prior to hot-forging is an area which is deemed to have significant energy savings potential. In conventional forging, preheating of the billets is typically achieved using convection gas-fired furnace. However, the lower rates of heat transfer to the work piece and the need for heating the furnace as well as the work piece makes the heating process longer and highly inefficient. Over the past few years, other heating techniques using high-speed convection furnaces [1, 2] and induction furnaces [3-5] having higher heat transfer rates have also been developed, but they provide minimal improvements and often bear certain disadvantages. Induction furnaces, for example, provide efficient heating;

however their use is limited by higher equipment costs and the geometry of the metal stock being heated. In addition, the induction furnaces often have coupling problems with aluminum alloys that accounts to more than 50% of the entire non-ferrous alloy forging volume produced in US each year. Considering the inadequacies of the existing heating techniques, Oak Ridge National Laboratory, along with other industrial and university partners have developed a new hybrid infrared heating system [6] that permits rapid and uniform heating of aluminum alloy billets prior to forging. Rapid Infrared (RI) heating has been proven to reduce the heating times by an order of magnitude, decrease energy consumption by factor of three and produce forgings with enhanced metallurgical and mechanical properties. Field testing of this hybrid infrared system in full-scale production setup has demonstrated cost savings up to 40-50% through reduced energy consumption, increased throughput and improved consistency in the process and quality of the product. The present paper discusses the principles underlying this new technology, provides energy and cost saving comparison between this and the conventional convective heating technique and explains the property enhancement in aluminum alloys using rapid heating.

EXPERIMENTAL

A. Hybrid infrared heating system

A full-scale production continuous-belt infrared furnace was designed on the basis of preliminary rapid heating trial runs performed with a batch-type drop bottom infrared furnace (Figure 1) located at Oak Ridge National Laboratory. The batch-type furnace is an 88 kW unit consisting of two halves, the upper half carrying an array of tungsten halogen quartz lamps and the lower half with a drop-down arrangement used to load specimens into the furnace. The main body of the upper and the lower halves is made of water-cooled stainless steel plates lined with fire brick. Figure 2 shows the temperature profiles recorded during rapid heating of 2.25 inch-diameter, 6-inch-long AA 2618 billets in the batch-type furnace. Unlike convection gas-fired furnaces, where a billet would take at least 1.5-2 hrs to get to the forging temperature, infrared furnace takes only 16 minutes.

Figure 1. Batch type drop bottom infrared furnace

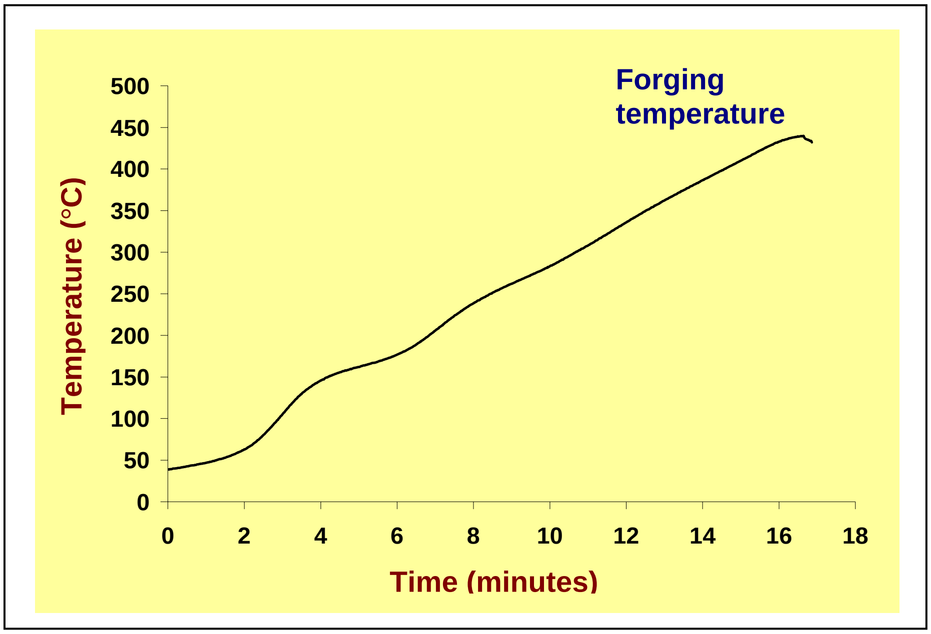

Figure 2. Temperature data for rapid heating of AA 2618 billet heated in batch-type infrared furnace

The hybrid rapid infrared (RI) furnace is a customized furnace designed for production-scale heating of billets. It is a 77 kW unit (Figure 3.) designed with an optimized combination of both radiant and convective heating. The term “hybrid” is derived from this unique combination of heating modes. The radiant part of heating is delivered through the short-wavelength (0.78 ~ 2.0 μm) infrared radiations emitted by heating an array of tungsten-halogen filaments to very high temperatures (in excess of 2200°C). The heat flux Q, from heated elements is given by Stefan-Boltzmann’s law,

$$Q = \sigma\varepsilon\left(T_f^4 - T_s^4\right)$$

where, σ is the Stephan-Boltzmann coefficient, ε is the emissivity, T_f is the filament temperature and T_s is the surrounding temperature.

Due to very high temperatures, the heat fluxes resulting from these filaments are nearly an order of magnitude higher than conventional heating elements. Such high fluxes, together with the low thermal mass of these filaments provide extremely fast heating rates, reducing the heating cycle time (Figure 4). Once the surface is heated, the high thermal conductivity of the aluminum (about 4 to 5 times that of steel) causes the heat to be conducted quickly to equalize the temperature across the billet. For a continuous production operation, the equalization of temperature is further aided by convection heating, which is delivered by blowing air at certain velocities to force the trapped heat between the elements and other furnace surfaces across the billet. The radiant heating and convective heating are further optimized by controlling the belt speed, which in turn depends upon the geometry of the component being heated. For example, for the system installed in a full-production set up, the nominal belt speed for heating 2.25 inch-diameter, 6 inch-long AA 2618 billets is 3 inch/min. Such belt speeds provide uniform and consistent heating of billets with exceptionally higher throughputs.

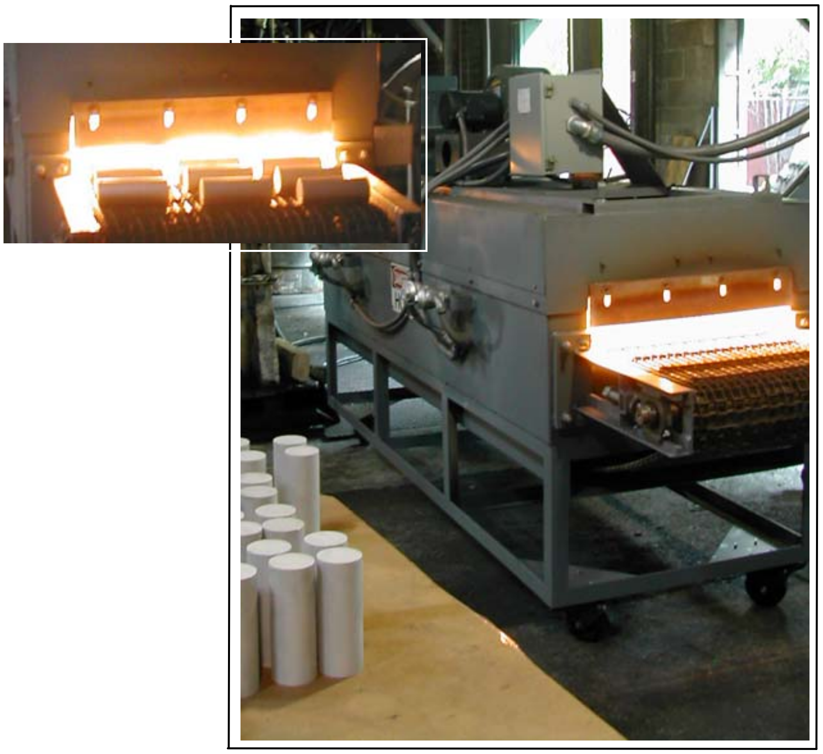

Figure 3. Hybrid Rapid Infrared furnace installed in a production setup

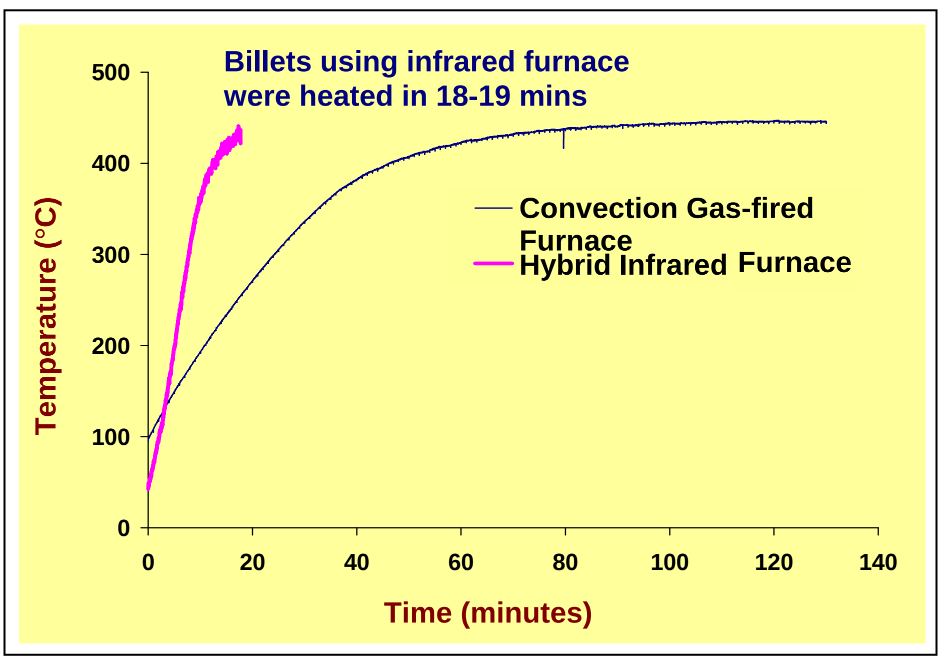

Figure 4. The time required to heat 2.25-inch-diameter x 6-inch-long, AA 2618 billets using a conventional gas fired furnace and using the hybrid infrared furnace

B. Materials Processing

In an effort to study the effects of rapid heating on the microstructural and mechanical properties of forgings, two sets of specimens (Specimen sets I and II) were produced. Specimen set I consisted of 2.25 inch-diameter, 6-inch-long aluminum 2618 alloy billets (Table 1) that were preheated in a conventional convective furnace, upset forged with a 2:1 reduction ratio and solution heat-treated and aged in a conventional furnace to a T61 temper. Specimen set II consisted of 2618 billets from the same lot which were preheated in the hybrid continuous infrared furnace, upset forged, solution heat-treated in the batch-type infrared furnace and aged in a conventional furnace to a T61 temper. The preheating and heat-treating conditions used to produce these two sets are given in Table 2.

Table 1. Chemical Composition of Aluminum 2618 alloy [7]

Wt%	Si	Fe	Cu	Mg	Ni	Zn	Ti	Al
Min	0.1	0.9	1.9	1.3	0.9	0.1	0.04	Rem
Max	0.25	1.3	2.7	1.8	1.2		0.1	

Table 2. Processing conditions

Specimen	Preheating prior to forging	Solution heat-treatment	Aging
I	Billets were heated to forging temperature (425 °C) using a conventional convective gas-fired furnace in 2.5 hours	Forgings were heated to the solutionzing temperature (530°C) and soaked for 2.5 hrs in a conventional furnace and quenched in boiling water	Forgings were aged at 200°C for 20 hrs in a conventional furnace
II	Billets were rapidly heated to forging temperature (425 °C) using the hybrid infrared furnace in 18 mins	Forgings were heated to the solutionzing temperature (530°C) and soaked for 40 mins in the batch-type infrared furnace and quenched in boiling water	Forgings were aged at 200°C for 20 hrs in a conventional furnace

RESULTS AND DISCUSSION

A. Energy savings and other benefits

The cost benefits associated with this system are primarily due to its efficient design and reduced cycle times. The hybrid infrared system is based on tungsten halogen filaments that convert electric energy into radiant energy (heat) with greater than 90% efficiency. These filaments can be switched on at room temperature and can come to full power in less than one second and provide an order of magnitude higher power densities as compared to conventional heating technologies. Such attributes of the filaments lead to shorter heating cycle times which drastically reduce the overall processing times for the billets. On the other hand, conventional furnaces, both gas and electric, take multiple hours to bring the aluminum forging loads to full temperature. The efficiencies of these type of furnaces are typically well below 25%, and when coupled with the large makeup times, the overall efficiencies are in the single digit percentages. Preliminary calculations have shown that a conventional gas-fired convection furnace takes approximately 1200,000 BTUs to heat a 500 lb load of billet to temperature in a 5-6 hour period while a hybrid infrared system would take 200,000 BTUs to heat the same load in almost one hour with a continuous belt type setup. Table 3 provides comparison for energy consumption using a continuous belt hybrid rapid infrared furnace and a conventional convective gas-fired furnace.

Table 3. Energy Consumption Comparison during Aluminum billet preheating

Attribute	Continuous-belt Hybrid Rapid Infrared Furnace	Batch-type Conventional Convective Gas-Fired Furnace[1]	Comments
Billet heating time[2] (mins)	20	240	Infrared heating provides an order of magnitude faster heating
Throughput (production rate) (lbs/hr)	350	80	Rapid heating using infrared increases the production rates 4 times
Energy used for Al-billet heating (BTU/lb)	500	1500	Energy consumption using infrared system is reduced by a factor of three
Overall efficiency of the system (%)	~ 30	~10	Infrared systems are three times more efficient than convection gas-fired furnaces

[1] Majority of the small and medium size forging shops in United States used fully-muffled or semi-muffled batch-type gas fired convection furnaces to heat aluminum alloy billets prior to forging.
[2] Heating load used for comparison purposes consists of 2.25-inch-diameter x 6-inch long aluminum 2618 alloy billets.

Based on the energy calculations shown in Table 3 and assuming that 1/3 of the 450 forgings companies in the United States heat 500 lbs of aluminum billets 3 times a week, the hybrid rapid infrared heating technology could result in energy savings of 2.21 x 10^{10} BTUs/year together with cost savings of 130 million dollars/year. The above estimated cost savings are based on the energies that are utilized only for preheating the aluminum alloy billets. They do not take into account the additional cost savings that could be achieved through reduced materials rejection and reprocessing costs. Infrared heating produces consistent and reproducible heating of the work piece, thus allowing the system to undergo full automation. Full automation will reduce rejection, produce less scrap and decrease labor costs as well.

Although the primary intention of this paper was to study the application of infrared energy for aluminum billet preheating, one of the remarkable findings during this study was its potential application for solution heat-treatment of aluminum forgings. Preliminary studies for solutionizing AA 2618 billets using batch-type infrared furnace demonstrated very large savings in time and energy. A 10-h solutionizing cycle could be reduced to 1.5 h, consuming only 20% of the energy currently used by conventional techniques. The details about this finding are still unknown and more work with this regard is underway and will be reported separately.

B. Properties enhancement

<u>Grain refinement</u>

Grain refinement is desired for improved fatigue resistance and toughness. Rapid infrared preheating for forging produced finer grain sizes (~27 μm) in solutionized specimens than those in specimens preheated in a gas-fired convection furnace (~40 μm) as shown in Figure.5. This grain refinement resulted from increased grain boundary pinning strength of intermetallic phase particles in the RI-processed specimens. Energy dispersive X-ray spectroscopy (EDS) identified that the intermetallic phase responsible for grain boundary pinning to be Al_9FeNi, Figure 6. This was also confirmed by X-ray diffraction. The shorter exposure of the RI-preheated specimens to high temperature kept more Al_9FeNi particles with much less ripening in the α-Al matrix, as can be seen in the micrographs of as-forged specimens in Figure 7. This provided stronger grain boundary pinning force in the RI-preheated specimens during the subsequent solution heat treatment as the matrix underwent recrystallization.

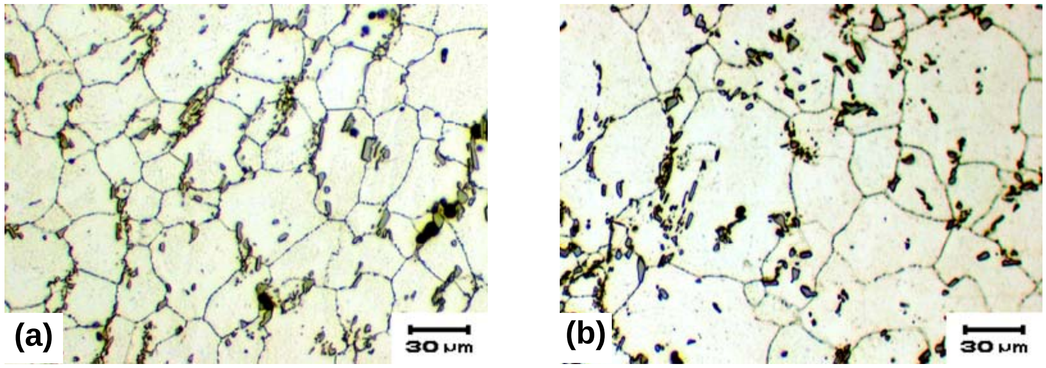

Figure 5. Micrographs of T61 forgings: (a) RI-processed specimen and (b) conventionally processed specimen.

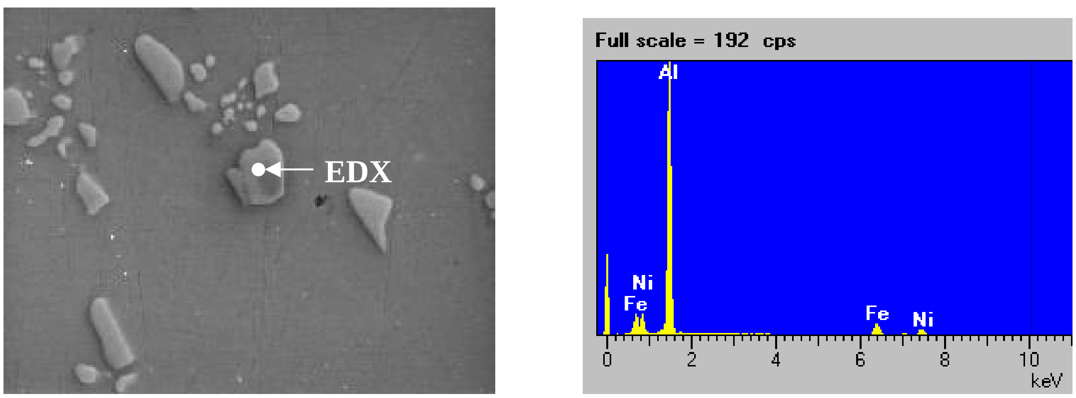

Figure 6. Intermetallic particles pinning at grain boundaries are Al_9NiFe confirmed by EDS.

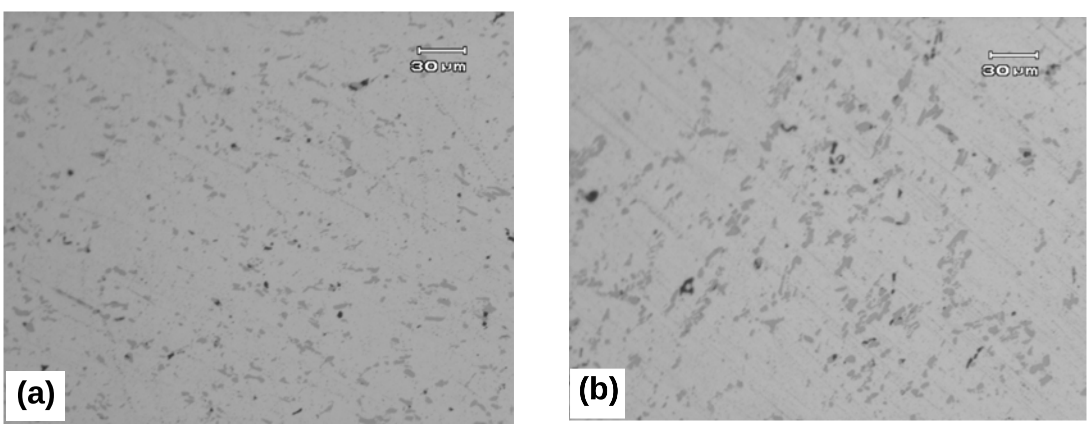

Figure 7. Micrographs of non-solutionized forgings: (a) conventionally forged specimen and (b) RI-forged specimen.

Improved mechanical properties

Higher T61 UTS and hardness values were obtained with RI-processed specimens than those processed conventionally as shown in Table 4 and Figure 8. The improved strength is caused primarily by stronger age hardening in the RI-heated specimens. Although the exact mechanism for the observed age hardening enhancement is still under investigation, it is known that nickel and iron may form stable compounds, such as $(CuFe)Al_3$ and AlCuNi, in 2618 and related Al-Cu-Mg alloys [8], depleting the α-matrix of copper, the element essential for the formation of the Cu-rich strengthening phases, i.e., the GP zones and S' (Al_2CuMg) [9]. In these alloys, the formation of $(CuFe)Al_3$ and AlCuNi can be minimized by the formation of the more stable phase Al_9FeNi, which scavenges the iron and nickel from the α-Al matrix. To assure this effect, the Fe:Ni ratio in Al-Cu-Mg alloys is adjusted to 1: 1, in line with the stoichiometry of Al_9FeNi [8]. However, Al_9FeNi, during prolonged heating, may pick up some of the copper, possibly releasing some iron and/or nickel, which may cause weakening of age hardening via formation of $(CuFe)Al_3$ and AlCuNi. The latter is believed to result in conventionally solutionized specimens.

Although not discussed in this paper, specimen that was RI-forged and conventionally solutionized had grain sizes similar to those of specimen II, but had a hardness comparable to that of specimen I (Table 4). This suggests that the achieved grain refinement does not significantly contribute to the strengthening. However, the grain refinement did improve the fatigue resistance as seen in Figure 9, which shows the S-N curves for the RI-processed and conventionally processed specimens.

Table 4. Process conditions, grain size and hardness of AA2618 forgings

Specimen	**Forging**	**Solution Heat Treatment**	**Aging**	**Grain Size[1]**	**Hardness[2]**
	425 °C	530 °C	200 °C	(μm)	(HRB)
I	Conventional	Conventional	Conventional	40	59.5
II	IR-preheating	IR, 40 mins	Conventional	27	67.7

[1]Grain size measured by linear interception. Listed are transverse cross-section grain sizes.
[2]Determined on transverse cross-section.

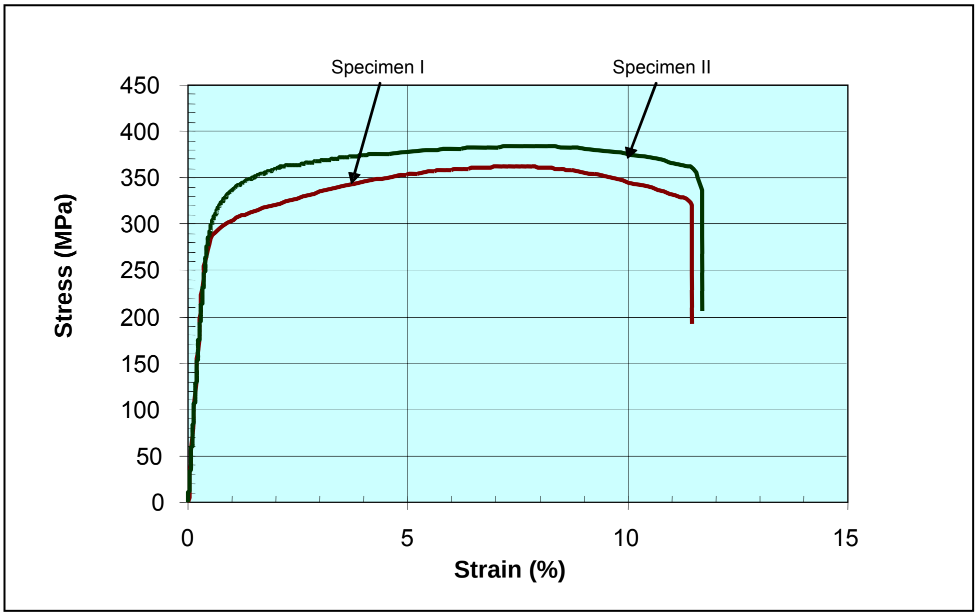

Figure 8. Stress-strain curves of specimens I and II. The tensile tests were performed at room temperature using 2.5 mm thick flat specimens 6.0 mm in width and 15 mm in gage length, cut longitudinally from the center of the forgings.

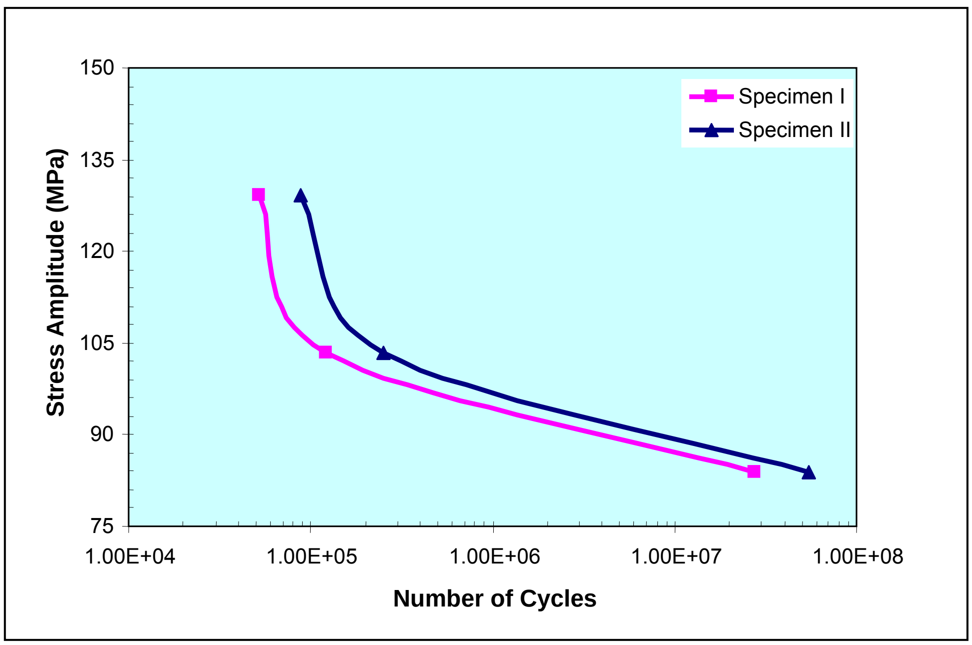

Figure 9. Stress amplitude vs. number of cycles of heat treated specimens under tension-tension loading condition with mean tensile stress at 180.8 MPa. The geometry of the fatigue test specimens is the same as the tensile test specimens described in the captioning of Figure 8.

CONCLUSIONS

Rapid infrared (RI) system offers a low-cost, energy-efficient heating methodology for preheating aluminum billets during forging. Implementation of this system in a full-production setup has demonstrated significant energy and cost savings through reduced billet preheating times and increased production rates during the forging operation. Along with energy savings, RI heating has also revealed remarkable metallurgical improvements such as increased strength and improved fatigue properties in solutionized forgings. Improvement in strength and increase in life of forgings is highly desirable for critical components used in automotive and aerospace applications. Thus, RI infrared system provides rapid and efficient heating along with unique capability of controlling the metallurgy of the forgings. In addition, RI also offers potential application in other thermal processes such as joining and heat-treatment and is also deemed applicable for processing other materials such as steel, titanium alloys and nickel and cobalt based alloys. Introduction of this technology in metal-forming industry will not only lead to significant energy savings, but will also increase the competitive stance of US industry.

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