

INFRARED HEATING OF FORGING BILLETS AND DIES

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ABSTRACT

Current heating technologies utilized by the forging industry for the preheating of both aluminum billets and forging dies are primarily: (1) gas or electric convection furnaces, (2) direct gas flame, (3) electric calrod radiant and (4) gas radiant heating. All of these heating methods require considerable shop floor time. In fact, die heating is often omitted or performed incorrectly which results in premature failure of the impression dies as well as increased scrap. Infrared heating which overcomes many of the problems associated with conventional heating is being investigated and implemented by the forging industry. Infrared heating of aluminum forging billets has shown drastic reductions in heating times and product microstructures with 1/6 the grain size of that achievable with conventional heating methods. In the studies of infrared die heating,

large dies can be preheated to 200 to 300C (392 to 572 F) in less than 30 min. Present industrial heating technologies are compared with infrared billet heating and die preheating.

INTRODUCTION/BACKGROUND

Aluminum alloys billets are heated for forging with a wide variety of equipment; electric furnaces, fully muffled or semi-muffled gas furnaces, oil furnaces, induction heating units, fluidized bed furnaces, and resistance heating units. Gas-fired, semi-muffled furnaces are the most widely used. Both oil and natural gas furnaces must use low sulfur fuels (1).

Induction, resistance, and fluidized bed heating are the preferred heating methods used in the forging of aluminum alloys in cases where forging processes are highly automated, which necessitates large part quantities. Induction and resistance heating are usually limited to simple bar stock. Fluidized bed, induction, and resistance heating have many materials handling restraints (1).

Aluminum alloys have a relatively narrow temperature range for forging which necessitates precise temperature control in preheating. The heating equipment should have pyrometric controls, which can maintain temperature within $\pm 5^{\circ}\text{C}$ (9F). Continuous furnaces typically have three zones: preheat, high heat and discharge. Most furnaces are equipped with recording and control devices and are frequently checked for temperature uniformity in a manner similar to that used in solution treatment and aging furnaces (1).

As a class of alloys, aluminum is considered to be more difficult to forge than carbon steel and many other alloys. Aluminum forging is typically performed at elevated temperature, approximately 426C (800 F) for 2014, 6069 , 7075, and 2024 Al. Heating of the billets, which are typically extruded or cast aluminum bar, can take up to four hours. Heating time is dependent on billet diameter and if the oven had been running for a prolonged period of time. A typical practice would be to load a gas convection furnace with aluminum billets the night before a forging run was to be performed (1). These long preheat cycles can and do cause extensive grain growth and dissolution of second phase particles. This in turn makes it impossible to try to control the metallurgy of the aluminum during the entire forging process. These long heating times also make it less practical to utilize these heating technologies for small batch sizes and for short lead-time jobs. In addition, the efficiencies of these types of furnaces are typically well below 25%. When coupled with the long heat up times, overall process heating efficiencies are in the single digit percentages. Preliminary calculations have shown that a gas convection oven takes approximately 800,000 BTUs to heat a 227-kg (500-lb) load of billets to temperature in a 4- to 5-h period. A hybrid infrared system would take 200,000 BTUs to heat the same load in less than 1 h, i.e. continuous belt-type setup.

The Forging industry employs approximately 45,000 people in the United States and Canada. The modern forging process is capital intensive and requires an abundance of heavy equipment for manufacture. Most forging plants are small businesses that generally employ between 50 to 500 employees each. A few larger facilities employ over 1000 people. These facts make it difficult for the vast majority of companies to utilize expensive heating equipment such as induction, resistance, and fluidized bed. Summarizing, gas-fired semi-muffled furnaces are the most widely used billet preheating method. These furnaces require long furnace lead times and long billet heat up times.

INFRARED HEATING OF ALUMINUM ALLOY BILLETS

Electric infrared heating, IR, provides a method for rapid heating of billets. This technology is based on tungsten halogen lamps, which can be switched on at room temperature and come to full power in less than one second. These heaters also provide an order of magnitude higher power density than conventional heating technologies, 20 to 40 W/cm² versus 2 to 4 W/cm². The IR lamps can also be shut down in less than 1 s and can convert electricity to radiant energy with greater than 90% efficiency. IR can heat a wide variety of shapes with good temperature uniformity. These attributes result in reduced preheating times and energy costs for IR billet preheating. It also provides the advantage of being able to heat a variety of shapes with no equipment modification. This is in contrast to induction heating which is generally limited to cylindrical shapes and requires a different coil for each type of billet. Despite these advantages, infrared heating is second only to induction heating in the rate of heating of cylindrical billets (2). Induction heating however typically requires five to ten times the capital cost when compared with the equivalent IR heating system.

LABORATORY TESTS

The objective for the laboratory testing of a billet IR heating system was to quantify heating rates attainable with an 88-kW panel heater. The panel is approximately 0.6 m² (6.4 ft²), shown in Figure 1. Heating rates for aluminum alloy billets were determined including the effects of furnace loading.

ALUMINUM ALLOY HEATING

The 2014 aluminum alloy was selected since it is a commonly forged aluminum alloy. Cylindrical, 5.23-cm (2.06-in.-diam) billets were heated to 425C (800F) in the panel furnace at 80 kW (90% of maximum power). Temperatures were measured using sheathed thermocouples inserted in drilled holes, and surface thermocouples mechanically attached with aluminum screws. Billets were prepared for heating in both a horizontal and vertical orientation.

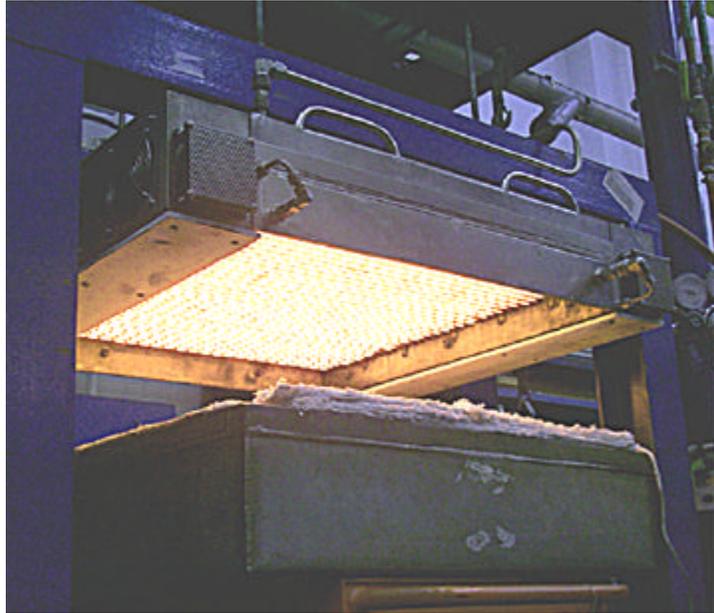


Figure 1. Electric infrared flatbed furnace, drop bottom batch type, utilized for both laboratory and industrial testing.

The heating curves for various locations in a cylindrical 2014 Al alloy billet in the horizontal orientation are shown in Figure 2. Also shown in the figure is power output over time, which is maintained at 90% during heating. The power then drops to 0 after 240 s and returns to a level of 20% after 290 s. The temperature control system provides the ability to heat at the maximum heating rate to the desired 425°C (797F) preheat temperature with no significant temperature overshoot. The thermal gradient in the horizontal orientation is less than 10°C (18F) as shown in the thermal profile in Figure 1. The temperatures measured using thermocouples fixed to the billet surfaces with screws are shown in Figure 3. The measured temperatures decrease with increasing angle from the top direction of the billet in the furnace. The measured temperatures after 4 min are also about 25°C (45F) higher than those measured with the internal thermocouples. This is due to direct heating of the thermocouples by the screw heads, which are heated by the incident infrared energy.

The heating of multiple billets was also evaluated to determine typical variations in temperature between billets. During the heating time of about 6 min, the internal temperature of both billets are the same and the surface measurements are somewhat higher, in both billets for the reasons described above. After 400 s of heating the temperatures are stabilized, with the temperature of the billet at the center location at about 15°C (27F) higher than that of the billet at the corner. This is attributed to greater thermal convection heat losses for the billet at the corner location.

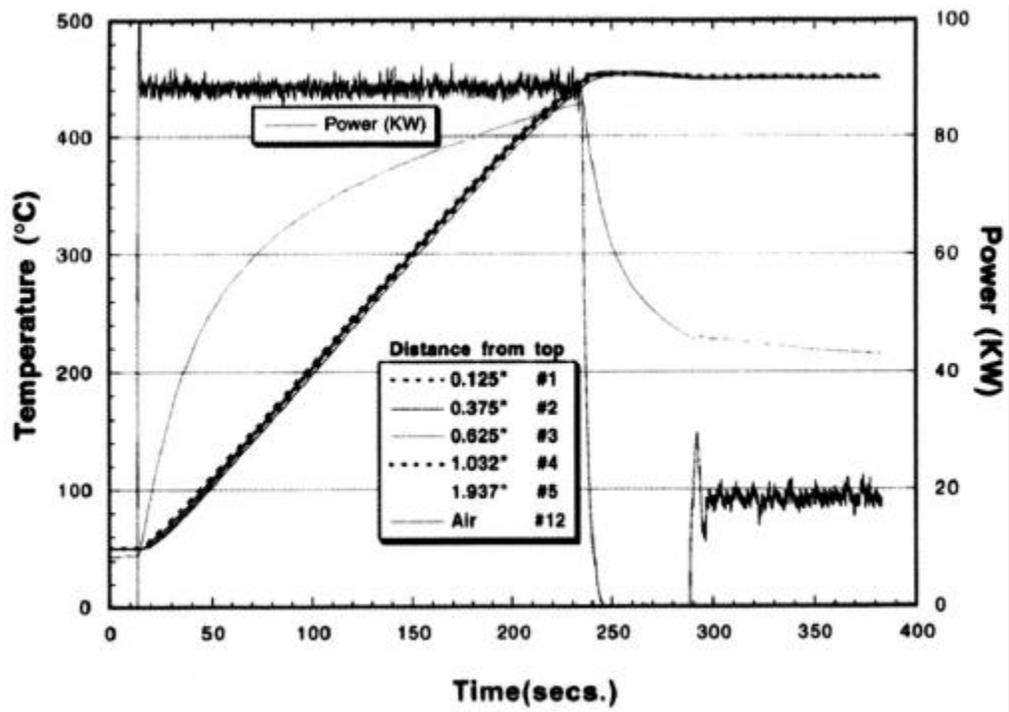


Figure 2. Radial heating curves for a 2014 Al bar in the horizontal position.

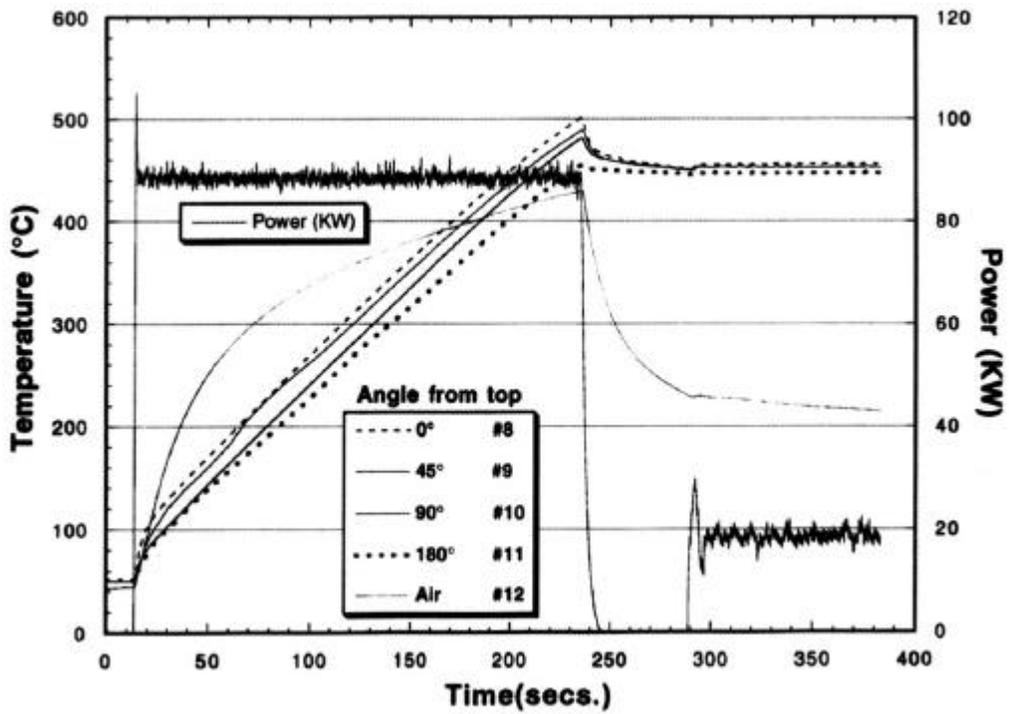


Figure 3. Circumferential heating curves for a 2014 Al bar in the horizontal position.

INDUSTRIAL TESTING

After completing the laboratory tests, the infrared heater used in this study was sent to Queen City Forging Company (QCF) to heat and forge aluminum billets in the field. The infrared furnace was operated at only 65% of its power capability, because of some shop utility limitations. Running the infrared furnace at these power levels would ensure a lamp lifetime in excess of 5000 h. The part being manufactured was described as a “rocker”, used in an industrial sewing machine. Input weight is 0.26 kg (0.57 lb). Net weight is 0.14 kg (0.313 lb). The part is approximately 20.32 by 2.54 cm (8 in. long by 1 in. wide). It is symmetrical across the parting line with significant thickness variation from end to end. This includes variation from a thin “H” beam connecting section, with an average 0.3175 cm (0.125 in.) thickness, to a center boss with a 5.715 cm (2.25 in.) thickness, across the parting line. Normal operations call for the preform to be finish forged in one heat. The part is then cold trimmed and sent to heat treatment.

QCF uses a gas-infrared-based heating system. Therefore a direct comparison was possible between gas-fired infrared and the electric infrared. Full furnace loads of aluminum billets were heated and forged in both infrared-based systems. The heating rates are shown in Figure 4. It was found that a cold electric infrared furnace full of billets could be heated to temperature and forged in approximately 12 min. This is less than half the time it would take to just heat the billets in a gas fired convection furnace. Data taken at QFC below shows electric infrared is highly controllable and able to reach forging temperatures in approximately one-third the time of gas infrared. Additional problems were observed with the gas infrared, which may or may not be typical, which include; the gas flame extinguishing when forging started and overheating of the unit.

As can be seen in Figure 4, electric infrared preheated the aluminum performs in less than half the time of gas-fired infrared and an order of magnitude faster than convection, typically an hour.

Upon return to the Oak Ridge National Laboratory (ORNL), a metallurgical analysis was performed on conventional, gas-fired infrared, and electric infrared heated and forged parts produced at QFC.

COMPARISON OF FORGED PARTS PREHEATED USING ELECTRIC INFRARED AND GAS

The metallurgical analysis was performed to determine if there were any significant differences in the microstructure of the parts processed using electric infrared versus the parts processed using gas infrared. It was determined that there is a microstructural difference. Further investigation showed that the grain size in the parts preheated using electric infrared was significantly smaller. Figures 5 and 6 compare the aluminum microstructures of gas and electric preheated, 2014 Al billets following a high-deformation rate forging.

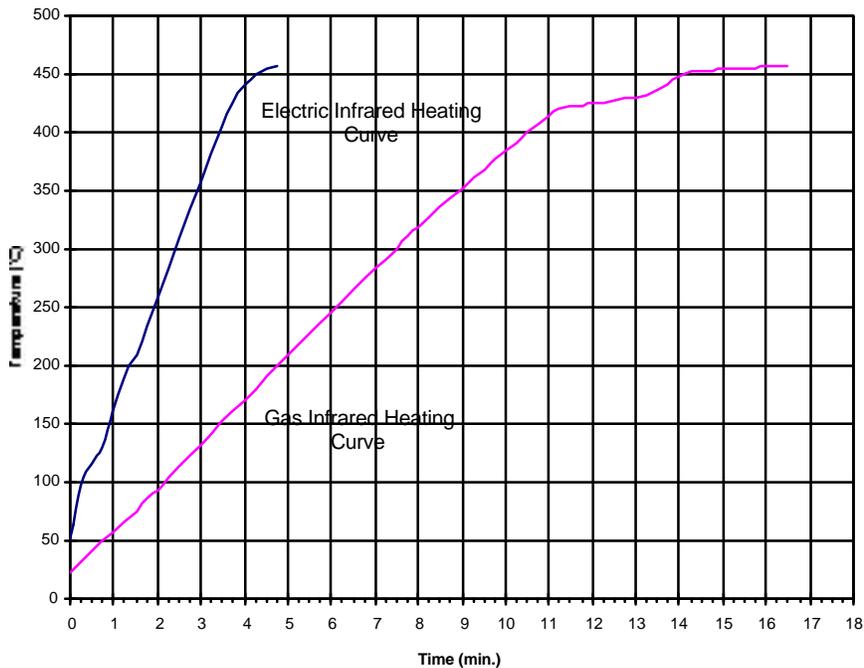


Figure 4. Heating curves produced at Queen City Forging Company, flatbed electric infrared system compared to gas-fired infrared.

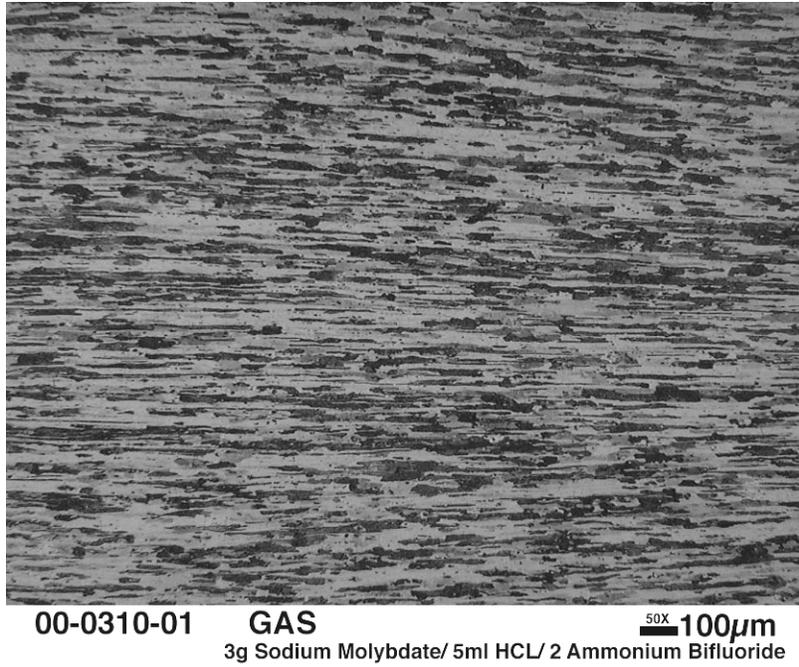


Figure 5. Microstructure of gas-heated and forged aluminum.

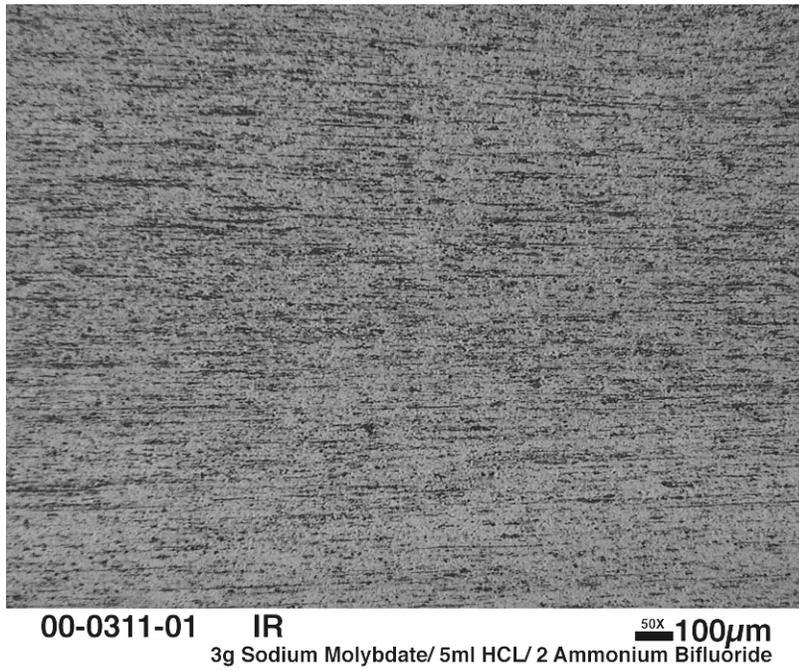


Figure 6. Microstructure of electric infrared-heated and forged aluminum.

As can be seen in Figures 5 and 6, the rapidly heated electric IR heating developed a finer microstructure.

A final T-6 heat treatment, 502C (935 F) for 40 min followed by a water quench, 60 to 82C (140 to 180 F), and aged at 171 C (340 F) for 10 h. These forged microstructures revealed that final grain sizes of the rapidly heated material were approximately one-sixth the size of a gas infrared-heated material. A comparison of the microstructures is shown in Figures 7 and 8.

As can be seen in the above figures, there is a drastic grain size reduction. This grain reduction technique was a serendipitous consequence that resulted during our efforts to improve energy conservation through shortened cycle times. Therefore, this result was not studied in great length but initial fatigue results suggest an enhancement as expected. Therefore, the infrared preheating technology allows for real time preheating of aluminum forging stock, minimizes grain growth, saves energy, and allows for fabrication of an enhanced microstructure part.

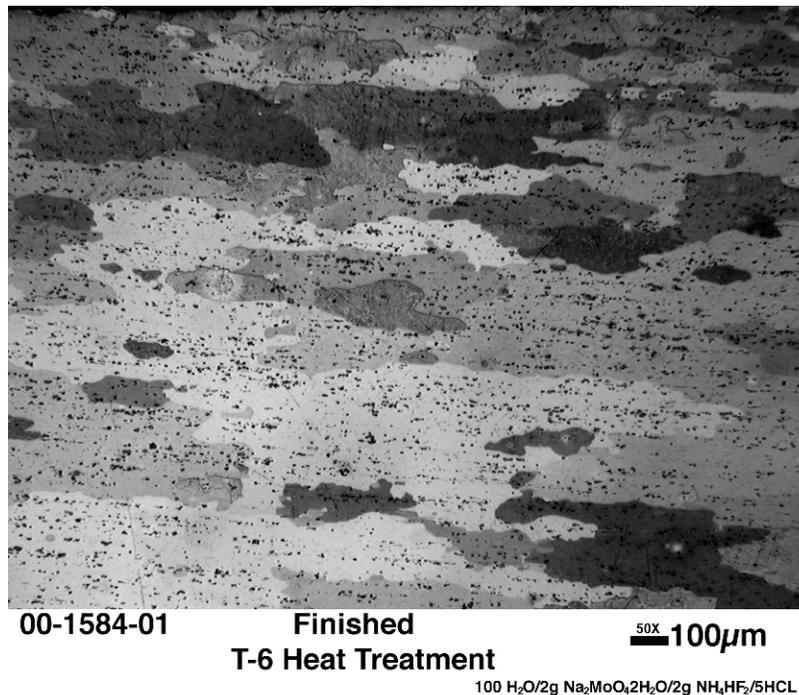


Figure 7. Microstructure of a gas infrared-heated, forged, and T-6 heat-treated aluminum part.

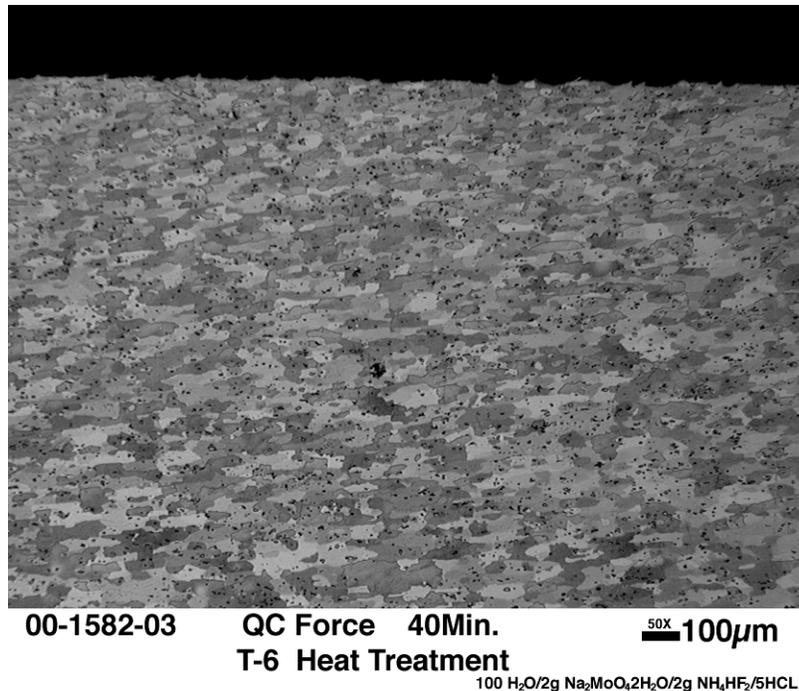


Figure 8. Microstructures of an electric infrared heated, forged, and T-6 heat-treated aluminum part.

DIRECT ENERGY SAVINGS

For a standard gas convection furnace 800,000 BTUs are required to heat 227 kg (500 lb) of aluminum billets. A hybrid infrared system, combining radiation and convection heating, such as the one described above, takes 200,000 BTUs to heat the 227 kg (500 lb) of billets. If one assumes that one-third of the 450 forging companies heat comparable loads of aluminum billets three times per week and, if there were full market utilization, there would be 23,400 loads/year with energy savings of 600,000 BTUs/load. A similar calculation could be made for titanium forging which requires twice the temperature of aluminum and has a production volume of approximately five times larger. The required BTUs per load for titanium would more than triple while that of the hybrid infrared would only double due to the better heat transfer. This better heat transfer is due to the 2200 °C (4000 °F) source temperature of the IR lamps versus a gas heated surface radiator.

DIE PREHEATING

Infrared heating permits the rapid heating of dies with good uniformity. The use of infrared heating offers a practical industrial method for reducing die preheating times and minimizing the energy costs of die preheating.

In order to demonstrate the applicability of infrared for die preheating, KomTek provided a production die instrumented with embedded thermocouples. This die was heated with the 88-kW electric infrared flatbed furnace during laboratory testing. Die preheating times and thermal profiles were measured over a range of preheat temperatures using the infrared panel heater which operates at a maximum output of 88 kW. This testing was conducted to optimize the heating process while ensuring the dimensionality of the die was maintained. Figure 9 shows a typical heating cycle on a $30.5 \times 35.5 \times 16.5$ -cm ($12 \times 14 \times 6.5$ -in.) die.

As seen in Figure 9, the surface of the die can be heated to of 300°C (572F) in less than 20 min. The results of this study show that infrared preheating of a die can be performed reproducibly with shorter heating times than those obtained using more conventional means. A “rule of thumb” for conventional heating of steel is 30 min per inch of thickness, which in this case gives a heating time of more than 3 h.

In addition to the possible savings in heating time and energy, the infrared panel heater has other practical advantages. The furnace itself can be brought to full power in a matter of seconds so there is no need to maintain a hot furnace in an idle condition. Also the heater itself is mobile and can be used to heat a die in place. If the heating of a die within a forging press is considered it is necessary to account for thermal conduction heat losses to the die holder, if any.

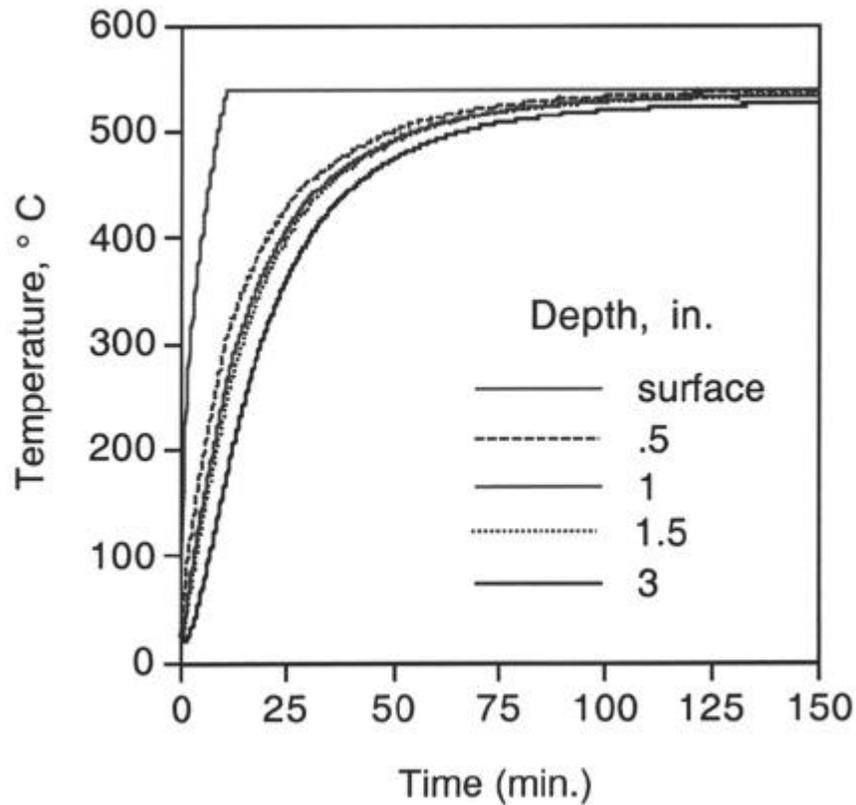


Figure 9. Temperature measurements for die heating at 80% of furnace power to a surface temperature of 538°C (1000°F) and then holding the surface temperature at this value.

The limiting step in heating this die and similar size or larger size dies is clearly the thermal conduction through the die. If it is possible to heat the surface to a higher temperature than the normal die preheat temperature for a limited period of time, then die preheat times can be further reduced by a significant amount. For example, if the desired die preheat temperature is 315°C (600°F) and the surface temperature has an upper limit of 538°C (1000°F) to avoid over-tempering, then the die preheat time to through-heat to at least 301°C (575°F) is reduced from 80 min to only 19 min. Alternatively, if the desired die preheat temperature is 315°C (600°F) and the surface temperature has an upper limit of 425°C to avoid over-tempering, then the die preheat time to through-heat to at least 301°C (575°F) is 28 min. Through programmed control of the heating power, the surface temperature could be reduced toward the end of the preheating to obtain a more uniform temperature prior to forging. This would result in only a small increase in the overall heating time.

This laboratory-based study of infrared heating of forging dies was able to make the following conclusions:

1. Infrared heating provides reproducible preheating of steel forging dies.
2. The preheating times are significantly less than conventional methods.
3. The limiting heat up time in die preheating is governed by thermal conduction through the die thickness.
4. Methods to dramatically reduce die preheating times are available if the die surface temperature is permitted to exceed the die preheat temperature for short periods of time.

INFRARED INSERT HEATER IN THE FIELD

Based on the above results, an infrared insert heater was designed to simultaneously heat the upper and lower dies in a hammer forge. A unit was fabricated at ORNL and put into testing on November 1999 at KomTek in Wooster, Massachusetts. The system in use at KomTek is shown in Figure 10, preheating in a hammer forge.



Figure 10. Oak Ridge National Laboratory insert heater preheats hammer forge dies at KomTek.

This system was designed to simply plug into a standard welding outlet receptacle and begin preheating in seconds. Initial testing of this heater in an ORNL forge revealed that

it could preheat 25.4-cm-thick (10-in.) platens to 204°C (400°F) in approximately 10 min. The system converts electrical into radiant energy in excess of 90% efficiency and goes from cold to full power in less than one second. The feedback received from KomTek after using the unit for eleven months in their shop was outstanding.

INDUSTRIAL FEEDBACK

The prototype die heater assembly was used 8 to 10 h/day continuously for 11 months. The production environment of the hammer forging operation was dirty and under continuous vibration due to the hammer blows. The heater operated in this environment for eleven months, only requiring 2 of the 12 infrared lamps to be replaced at approximately \$40 each. The reliability of the unit was extremely impressive even though the lamps were exposed to the harsh industrial environment of a production forge shop. This heater had been designed based on extensive testing of a control scheme using the interior lamp temperature versus exterior lamp temperature.

The vice president of Operations at KomTek stated that “It became very clear immediately after the prototype unit was put in service that the quality of product improved. After 11 months we have a better understanding of why this was the case. One of the primary reasons was that the ability to apply a consistent coating of die face lubrication between forgings, and sometimes even between blows, was greatly enhanced. Since the die impressions were so uniformly heated to the same temperature, including draft walls, application of the aerosol die lubrication to a uniform and consistent depth was extremely easy. Previous methods of die heating never produced this result. Only one other die heating method, gas-fired infrared, produced comparable results with lubrication, but it required three to four hours to get the die blocks hot enough to start forging. The quartz infrared system takes, at most, 30 min. The application of consistent lubrication results in much less sticking, less rework, and less die face wear”.

ENERGY SAVINGS

One unanticipated aspect of using the infrared heating system was the reduced energy consumption. Heating the die blocks faster allows us to produce more parts in a given time period. Prior to using the infrared system, the furnace that keeps the forging stock heated ran at full capacity during the entire shift, but when the die heater was used, more forging were produced in that shift without having to run at full capacity.

CONCLUSIONS

Electrical infrared-tungsten halogen lamps have been shown to be industrially robust enough to survive the conditions experienced in a hammer forge shop. The technology

has been shown to save energy and time through rapid preheating of aluminum forging billets and rapid preheating of forging dies. The rapid preheating of aluminum has resulted in a forged product with enhanced fatigue properties at one third the energy cost while the rapid uniform preheating of forging dies has allowed for reduced scrap and die life extension. In the forging of a particular super alloy part, the use of the infrared insert heater doubled the die life. Therefore, one die rework was not needed saving more than \$3,000. An insert heater has a capital cost of approximately \$3,000 for a 30.5 by 61 cm (12 by 24 in.) unit, as used at KomTek.

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