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Recent and ongoing research concerned with homopolar generators operated in a pulse mode and making use of kinetic energy storage principles has led to the application of these techniques to forging billet heating. Cylindrical billets of AISI-SAE 1022 and 1042 ferritic steels, Type 304 austenitic stainless steel, and Type 6061 aluminum were heated to their forging temperatures within 2 to 4 seconds. Although not used during the study, a feedback control system for the generator should make it possible to deliver billets at a uniform temperature. Scale loss with the ferritic steels was less than 0.5 pecent. Heating of billets is uniform over their cross sections. Energy delivery efficiency of the homopolar pulse billet heating process is insensitive to billet aspect ratio and resistivity. The process appears to be attractive for heating nonmagnetic billets or materials having high resistivities, but would likely be more expensive than induction heating if used to heat ferritic steel billets.

THIS REPORT DESCRIBES RESEARCH done under National Science Foundation Grant MEA-8111918. The purpose of the work was to explore the technical and economic feasibility of a new method of heating metal forging billets, the homopolar pulse billet heating (HPBH) process. In this process, one or more large unidirectional pulses of electric current are passed through the billet, raising its temperature to the proper range for forging. Current pulses are delivered by a homopolar generator (HPG). When operated in the pulse mode, present HPGs are capable of delivering megampere-range current pulses of several seconds' duration. Speed of heating is one of the principal advantages of the process.

Some of the specific objectives of the research were

1. to determine the proper HPG rotor speeds, field excitation currents, and fixture clamping forces and the resulting discharge currents, voltages, powers, and energy transfer efficiencies to heat billets of ferritic steel, stainless steel, and aluminum to their respective forging temperatures;
2. to determine the discharge-to-discharge repeatability of the HPBH system as shown by the variation of peak temperature of successive billets;
3. to vary the rise time and shape of the current pulse and observe the resulting variation in billet heating rate;
4. to study the effects of billet diameter and aspect (L/D) ratio on the heating requirements;
5. insofar as possible, to evaluate the HPBH process economics and compare them with the competing billet heating processes -- fuel fired furnace heating, induction heating, and direct AC resistance heating.

A billet heating fixture was designed and constructed to carry out these tasks. It consists of two flat axial-feeding electrodes supported in steel end plates that are guided and tied by connecting shafts and rods. One electrode is supported in a sleeve bearing and is actuated by a low profile, 20-ton (18.1-tonne) hydraulic jack. This movable electrode is retracted by four return springs whenever the hand pump of the jack is vented. The jack force is adjusted by means of a precision gage in the 10-ft (3-m) high pressure hose connecting the pump to the jack. Total jack stroke is 0.44 in. (1.11 cm).

The main advantages of the new billet heating fixture were (1) its ability to drop billets quickly into an insulated catcher after the heating pulse to determine the natural cooling rate in air, and (2) the axially-fed current feature, which eliminates the current constriction effect that would have been present with current entering a billet from radial electrode clamps, and thus improves the uniformity of current distribution in the billet cross section. The fixture was operated successfully in about 100 discharges during the project with electrode current densities as high as 125 kA/in.2 (19.4 kA/cm2) without significant electrode or billet end damage. Maintenance of the electrodes between discharges was limited to abrasive cleaning and degreasing by hand except in one case in which some melting of one electrode occurred due to inadvertent loss of hydraulic pressure during a discharge.

A Vanzetti two-color optical pyrometer was used to measure the surface temperatures of billets during heating and cooling. This instrument consists of an optical head that views a 0.2-in. (5-mm) diameter spot from a working distance of 24 in. (61 cm), a fiber optic cable that carries the signal to two different monochromatic filters, and sensor and logic circuitry that electronically converts the magnitudes of the filtered signals to temperature. Prior to using the optical pyrometer to measure the surface temperatures of heated billets, an experiment was run to observe its behavior when sensing the temperatures of several types of metal surfaces. Low carbon steel coupons, 0.1 in. (0.254 cm) thick by 0.5 in. (1.27 cm) wide, were gang milled to assure uniform size. A 3000-A voltage-regulated SCR power supply was used to feed a current of 1100 A through each specimen for 7.20 s. The pyrometer was aimed at the middle of one side of the specimen. Output of the pyrometer was observed for three surface preparations: polished, bead-blasted, and oxidized. The entire series of experiments was conducted in a transparent chamber which had been purged with nitrogen for five minutes before each trial to minimize any changes of the surfaces that might occur during the current pulse.

Measured temperature response was as expected. The polished specimen had a low emissivity and the highest indicated temperature; the grit blasted specimen had the highest emissivity and the lowest temperature; and the oxidized specimen, on which the scale was adherent, was intermediate.

The repeatability task was designed to determine the inherent variability of the 10-MJ HPG with its present open-loop controller to produce a short run of heated, nearly identical billets. A series of preliminary discharges was used to establish what at the time were believed to be appropriate HPG machine settings for the billets A campaign of ten billet heating discharges was then conducted.

The billets used in this task were AISI-SAE 1022 steel, 1.5 in. (3.81 cm) diam x 4.5 in. (11.43 cm) long. Temperature, current, and voltage data were recorded for all discharges. The standard deviation of the peak temperature was 109 F (43 C). This task was performed with open loop control. The generator's control system is now being modernized to permit feedback control.

Another task was conducted to examine the effect of specific material properties (e.g., density, resistivity, heat capacity, and phase transformations) on the HPG parameter settings required to heat billets of different materials, but having the same size and shape, to their appropriate forging temperatures. The materials tested included 6061 aluminum, 1022 and 1042 carbon steels, and 304 stainless steel. All of the billets were 1.5 in. (3.81 cm) diam x 4.5 in. (11.43 cm) long except for the 1042 steel billets, which were made 4.0 in. (10.16 cm) long to distinguish them easily from the 1022 billets.

A series of discharges was made with billets of each material to determine the proper HPG parameter settings to heat that material to forging temperature. From the data for voltage and current vs time, energies deposited in each material were calculated by numerical integration.

Our results indicate that one can make an initial estimate of the system parameter settings for heating billets of a new material by calculating the energy requirement using handbook values of mean specific heat, estimating the energy transfer efficiency from past experience and then controlling field excitation current to make fine adjustments in peak current, peak temperature, pulse length, and heating rate. This procedure is, in fact, the one which was used in the performance of these tasks, and more than two preliminary discharges were rarely necessary to arrive at system parameter settings that resulted in heating billets to temperatures within the desired forging range.

Microstructural examinations of billets of all four billets were conducted after heating. The normalized 1042 steel consisted of fine-grained ferrite and pearlite and was uniform from center to surface. After having been heated to 2320 F (1271 C), microstructures at the midplane of the billet show a network of proeutectoid ferrite outlining the former large austenite grains which formed on heating, and which now consist almost entirely of pearlite. These microstructural changes were very similar to those in the 1022 steel except that the 1042 steel contained almost no Widmanstatten ferrite. Also as in the case of the 1022 steel, there was little grain growth at the billet-electrode interface, presumably due to heat losses into the copper and consequently a lower peak temperature.

The 304 stainless steel experienced no observable microstructural changes anywhere in the billet as a result of heating to 2165 F (1185 C).

Likewise, the 6061-O aluminum showed no grain growth or other visible microstructural changes anywhere in the billet resulting from heating, even after heating to 1175 F (635 C), which is above the forging range for 6061.

Another task was conducted to determine the maximum heating and cooling rates expected in billets heated by the 10-MJ HPG using the billet heating fixture. Identical billets of 1022 steel were used. Rotor speed at discharge and electrode pressure were held constant throughout this series of discharges.

The energy delivery rate (power) during an HPG discharge, and therefore the billet heating rate, can be increased by increasing the field excitation current. Carrying out a discharge at a higher constant value of field current will result in a higher magnetic flux density in the HPG and therefore in a higher output voltage. It will also result in a higher voltage drop across the billet and a higher peak current.

An alternative method for raising effective power is to make use of the ability of the HPG controller to vary the field excitation current during the discharge. The discharge parameters used for the repeatability task were duplicated as nearly as possible, including the initial field current of 320 A. Beginning at 0.08 s after pulse initiation, however, by which time the current peak has already been reached, the field current was programmed to ramp to a final value of 500 A by the end of the pulse.

The effect of the increasing field current was to enhance the discharge current during the time interval between 1.0 and 2.5 s after discharge initiation and to decrease the duration of the discharge voltage pulse from approximately 4.0 to 3.5 s. These seemingly minor differences in current and voltage resulted in a net increase of power entering the billet that decreased its heating time from about 3.5 to 2.0 s. The peak temperature also increased slightly, because the shorter pulse time reduced both the system mechanical losses and the billet thermal losses during the discharge.

The most important effect of this increased power was a tripling of the maximum heating rate of the billets from 600 F/s (305 C/s) to about 1800 F/s (982 C/s), with no adverse metallurgical effects on the steel. Routine use of ramped field excitation current for billet heating appears to be desirable, since it results in more rapid heating and in improved energy transfer efficiency without increasing the rate of rise of current or the value of the peak current.

The effects of billet size and shape on energy efficiency, current distribution, temperature gradients, and heating rate were studied. Four sizes of 1022 steel billets were heated. The proper HPG settings were estimated knowing the energy requirements and the effects of billet resistance on transfer efficiency. For each of the three new sizes and L/D ratios, only one preliminary discharge was required to determine the final HPG settings. The ramped field mode of operation was used throughout this task to improve heating efficiency.

Calculations of effective heat capacity and resistivity were made based on data taken when each billet had reached 2000 F (1093 C). Close agreement was found among calculated effective specific heats, as had been expected. Energy losses by whatever mechanism are insignificant compared to energy inputs during rapid pulse heating, so the required energy can be accurately predicted using known values of specific heat, at least within the range of sizes and shapes of steel studied.

The effective resistivities for the four billets were also very similar, which seems to indicate that current distribution was uniform in all cases studied, regardless of size or shape. Uniform current distribution has been an important assumption throughout our study of pulse billet heating. The principal arguments justifying this assumption are (1) inductive effects are very small; (2) any nonuniformity in current distribution would tend to be self-correcting, due to local heating of the metal and redirection of current flow because of the positive temperature coefficient of resistivity.

Energy delivery efficiency was observed first to increase with increasing L/D due to more favorable billet impedance mismatching with the remainder of the circuit, and then seems to level off or even peak, due to the greater system mechanical losses with the more resistive high L/D billets associated with the longer time constant of the discharge waveform. This effect can also be observed in the length of time required for billets to reach 2000 F (1093 C). For an L/D of 6.0, this temperature is not reached for 2.17 s, already far past the maximum power point of the discharge. For L/Ds higher than 6.0, mechanical losses would dominate, causing a decrease in energy transfer efficiency. Since the range of the HPG time constant can be controlled by the machine design, it should be possible to custom design HPGs having optimum energy delivery efficiency for any particular resistive load.

An economic comparison was made between the homopolar pulse billet heating process and the two primary means of billet heating, gas-fired furnaces and electric induction heating. Unstable fuel prices, slow heating rates, and excessive scale loss are the major disadvantages of furnace heating. Induction heating is less efficient with nonmagnetic metals and is highly dependent on billet geometry, since heat generation is localized near the surface of the billet due to the skin effect. On the other hand, the HPBH process requires a large capital investment, and its repetition rate is limited by the motoring time of the HPG, which is typically about two minutes. At present, the process appears to be economically attractive for heating reactive and refractory metals and other nonmagnetic metals, or in cases in which the HPG can also be used for such other applications as welding or powder processing.