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Forming operation of metastable austenitic stainless steel and inductive recrystallization of strain induced martensite

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ABSTRACT

The temperature assisted recrystallization of strain induced martensite, after deep drawing metastable austenitic stainless steels, is a well known process for increasing the formability through multi-level deep drawing applications. State of the art recrystallization processes, using continuous annealing or vacuum furnaces, have the disadvantage of variable grain growth over the part cross section. This paper shows how the heat treatment by using an electro magnetical field, provided through different types of induction coils, can affect material properties positively. The studies were carried out on AISI 304 specimens with varied strain rates

1. Introduction

During the forming process of metastable austenitic steel sheets, e.g. AISI 304, a transformation into strain-induced martensite can be observed in certain areas – like the transition zone between flange and wall that is subjected to compressive strain.

When considering the first forming step of complex part geometries, e.g. a kitchen sink, this formation of strain-induced martensite can be both beneficial and unfavorable for the successive forming processes. A positive influence of this TRIP-effect can be noticed in areas that have to transmit high forming energies [1]. All other areas, on the other hand, are affected adversely, as the presence of martensite significantly reduces the drawing ratio. Delayed cracking and hydrogen embrittlement are other difficulties that emerge in areas with high amounts of strain-induced martensite. This phenomenon is dependent on the chemical composition of the sheet material, the tool temperature, the applied lubrication system and the forming velocity. The appearance of delayed cracking in metastable austenitic steels can already occur after a few hours as well as some days. This negative effect can be avoided by either suppressing the formation of strain-induced martensite–this can be achieved by selectively heating certain tool areas–or by including a recrystallization annealing step after or in between the drawing steps [2].

Once a drawing ratio is reached that marks the limit of deformability of an austenitic stainless steel, many austenitic stainless steel processers rely on an intermediate annealing operation to produce a ductile microstructure. This procedure ultimately enables the realization of most complex part geometries that are made of metastable austenitic steel. Typically such – rather laborious – recrystallization processes are carried out in continuous furnaces or vacuum furnaces, with or without protective atmospheres. The components can be further processed immediately after they have cooled down. During the intermediate annealing it has to be ensured, however, that a grain size distribution between 8 and 8.5 ASTM [3] is achieved that is ideal for the further forming processes, as well as the part's surface. In addition to the mechanical technological properties, also the suitability for being polished is determined by this. Increased grain growth, that takes place at high temperatures and long dwell times, results in a surface roughening and the so-called orange skin. The furnaces mentioned before have the disadvantage of high investment costs, as well as increased space and energy requirements. A chance to improve these negative aspects of conventional furnace concepts, not only for the processing of austenitic stainless steel [4], is the incorporation of the inductive heating technology. The inductive heating technology, which is applied for the annealing of cold-rolled strips, has already been examined in detail [5].

In [3] is already documented the possibility of partially recrystallizing austenitic stainless steel components with high amounts of strain-induced martensite, in order to facilitate successive forming operations and to positively influence the surface quality. These investigations set out to verify the applicability of induction heating technology for the recrystallization of locally strain-induced martensite in three-dimensional components. The adjustability of the grain size, onto an optimum level for deep drawing applications, through an inductive recrystallization process is one of the main interest of this research and is carried out by varying either induction technologies and process parameters.

2. Experimental setup and method

2.1. Test setup

Inductive heating is a high efficiency energy conversion process. Mains voltage is transformed within a convertor into a high-frequency current that drives an inductor. An alternating

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electromagnetic field emerges around the coils of the inductor. If an electrically conducting component part is situated close-by so-called eddy currents are induced on its surface. Electrical power is generated as a consequence of the part's electrical resistance and dissipated in thermal output. The part is heated. Hence, electrical energy is transformed into thermal energy at the point of intended use – the specimen. Inductive heating is a contactless process as the generator and the load have no physical contact.

The induction coil is made of highly conductive material - usually copper. In most applications water cooling of the coils is a non-negligible necessity due to the high currents [10]. The geometry of the induction coils determines the nature of the electromagnetic field and must always be adapted to the specimen's geometry. For axisymmetric parts cylindrical induction coils are preferential that produce a longitudinal electromagnetic field whose field lines are in parallel to the specimens curved surface area. For localized heating of surface areas, surface area inductors are generally available. The magnetic field lines are in normal direction to the surface [11].

For the heating of three-dimensional parts (e.g. kitchen sinks) the longitudinal induction coil has proved to be a reasonable compromise (see Fig. 1). The electromagnetic field can be established in the whole interior volume that is enclosed by the induction coils. This is of a vast advantage, specifically for deep drawn specimens. Due to the forming process subareas of the primal austenitic phase change to a martensitic phase with ferromagnetic properties. The electromagnetic field specifically concentrates in these areas as a consequence of their high permeability while the degree of heating in nonmagnetic areas is low. In the ferromagnetic areas, temperatures up to the melting temperature are feasible. Therefore, the recrystallization of the martensitic areas is possible very localized.

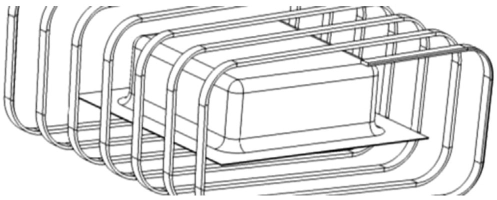

Fig. 1. Longitudinal field inductor.

For surface area inductors the distance of the inductor coils and the specimen is the main influencing factor for their effectiveness. Thus, it is not possible to generally heat goods with arbitrary shape with only one inductor. Fig. 2 shows how the shape of the inductor has to be adapted on the geometry of the part to be heated, in order to just heat those areas where high temperatures are necessary for recrystallization of martensitic structures. The realization of high heating rates and high localized temperatures is possible by using this inductor technology.

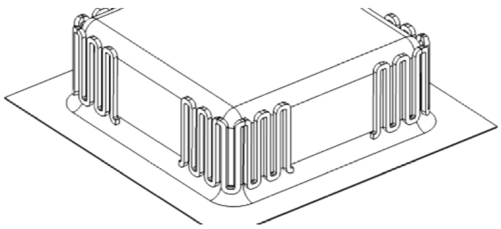

Fig. 2. Face inductor.

At the Institute Tools & Forming an experimental device has been developed providing a 10 kHz-convertor and a 100 kHz-convertor with nominal power of 160 kW and 120 kW respectively. Longitudinal and surface area inductors are available with varying geometries. Depending on the material composition, flat parts as well as axisymmetric parts can be heated to temperatures far beyond 1273 K [4].

2.2. Experimental procedure

In order to verify the ability of the inductive technology to recrystallize austenitic stainless steel components with locally increased amounts of strain-induced martensite, the strain conditions of a kitchen sink, made of AISI 304, were determined (see Fig. 3). These strain states were then transferred on to a smaller geometry, an axisymmetric cup. An increased formation of α' martensite can be noticed in the wall areas [6]. This is the same type of strain that predominates in the cylinder walls of axisymmetric cups. The process parameters for the inductive recrystallization by using a longitudinal induction coil, in order to determine the annealing parameters for a specific grain size, were determined based on these axisymmetric cups.

The obtained annealing parameters were then transferred to pre-drawn flat bar tension specimens, in order to associate an eventual increase of the drawing ratio during the final draw with this type of heat treatment. The acquired results can be transferred to large scale components, like a kitchen sink, and therefore constitute an alternative to conventional processes.

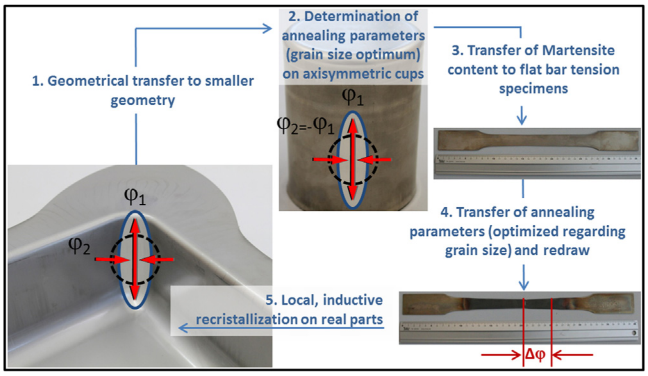

Fig. 3. Experimental procedure.

All experiments were carried out with the material AISI 304.

The fundamental experiments included three different part geometries that were heated with different inductors. For the longitudinal area induction an axisymmetric cup was chosen that was produced in a three-step drawing process (total drawing ratio $\beta = 2{,}4$). As the deviation of key process parameters highly influences the formation of α' martensite [6], it was ensured that all test specimens were drawn under constant conditions In order to quantify the amount of the strain-induced α'-martensite, in situ measurements were carried out in the wall area of the cup, using a Fischer Feritscope FMP30. The obtained measuring results, detected in Fe%, were subsequently adjusted to the correlating measured sheet thickness (see Fig. 4) by applying a thickness correction factor. According to [7], the measured amount of the ferromagnetic portion in the highly deformed areas equals the existent quantity of the strain-induced martensite. During the executed tests, the process parameters were altered in a way that α' values of 20–25 Fe% and 30–35 Fe% were achieved. This way the influence of the martensite amount on the rate of heating could be investigated. To validate the functionality of the recrystallization annealing of a longitudinal area inductor, the in situ measurements of the ferrite content were repeated after the heat treatment. The assessed components were heated to 600 K, 973 K, 1073 K, 1173 K, 1273 K and 1373 K–these temperatures were then held for 0 sec, 30 sec or 60 sec. The measurements on the part's surfaces were carried out with welded thermocouple elements, type N. As an initial step, the martensitic amount was reduced to less than 1% to confirm the functionality in principle of the inductive recrystallization annealing process. Components that featured a martensitic quantity less than this value were subjected to grain size analysis (according to ASTM E112) of their recrystallized austenitic structure. For the purpose of a comparison of the adjustable grain size with the reference heat treatment, annealing in a conventional