IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

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To cite this article: B. Nacke and A. Dietrich 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **424** 012058

9th International Symposium on Electromagnetic Processing of Materials (EPM2018) IOP Publishing
IOP Conf. Series: Materials Science and Engineering **424** (2018) 012058 doi:10.1088/1757-899X/424/1/012058

Potentials of single stage induction heating for press hardening of steel blanks

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Abstract

Due to growing challenges regarding crash-performance, CO_2 emission as well as increasing demand for lightweight construction, hot metal forming of car body parts has risen to one of the most important technologies for saving weight of a car body. During hot forming shaped blanks of steel are heated and austenitized at around 950°C and subsequently quenched for martensitic formation. Currently the heating is realized in roller hearth furnaces which allow only a slow heating and, therefore, a limited production rate. Induction heating of the blanks offers a big potential to increase the production rate dramatically and also to improve the energy efficiency. Only due to the fact, that the heated blanks typically are already pre-shaped with holes and cut-outs induction heating becomes a very complex task. The paper compares different possible induction heating methods (longitudinal heating, transverse flux heating, single stage induction heating, hybrid heating by induction and conventional heating). For the case of single stage induction heating a detailed numerical and experimental investigation in the frame of a recently completed research project is presented.

Keywords: induction heat treatment, hot metal forming, induction heating of blanks, strip heating

Introduction

Nowadays conventional heaters with oil or gas are mainly used in industry for the heating of high strength steel work-pieces. All of them are working by the principle of heat transfer through the surface. This principle has significant disadvantages and restrictions: limited power density, low speed of motion, large size of installations, originally intensive scale formation on the material surface because of long heating time, environmental pollution.

Beside all of these disadvantages the benefit of conventional heaters is the homogeneous heating of the work-pieces. At the same time, this big advantage limits the process variability. An inhomogeneous heating, which is necessary for applying different mechanical properties inside one work-piece, cannot usually be realized.

In comparison with conventional heating methods induction heating offers a lot of advantages, which are mainly based on the principle of direct heating within the heated material. The advantages are theoretically unlimited power density, short heating times, high efficiency, low floor space needs, high flexibility in processing, etc.

Recently different induction heating concepts for hot metal forming were investigated. The potential of continuous heating with longitudinal and transversal flux concepts is analysed in [1,2]. With those heating concepts it is possible to heat blanks up to the Curie temperature. The potential to heat blanks above the Curie temperature is described in [3,4] using single side induction heaters.

Induction heating concepts

Induction heaters can be used for a single-stage heating of work-pieces. The main advantage of induction heating is the fast and energy efficient heating, for holding they are less efficient. Therefore, induction heating for heating up the work-piece can be combined with conventional heating methods if holding or equalization of temperature is necessary.

There are two induction heating concepts for flat material. They differ by the direction of resulting electromagnetic flux provided by the induction coil - longitudinal and transversal flux. Beside the two variants for homogeneous heating also adapted induction heaters for local or inhomogeneous heating of the work-piece are available.

Longitudinal flux heating

For longitudinal flux heating an induction coil encloses the material to be heated, like a strip in Fig. 1. A current in the coil provides the electromagnetic field with a flux orthogonal to the cross section of the strip. By the electromagnetic field eddy currents are induced close to the surface of the strip which are closed in the cross section of the strip (shown as "S" in Fig. 1).

The depth of this current flow is influenced by different material properties and mainly by the frequency of the coil current. This depth is called penetration depth and is given by

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu}}$$

with ρ - specific electrical resistance, μ - permeability and f -frequency. Consequently, the induced current heats up the material by Joule heat.

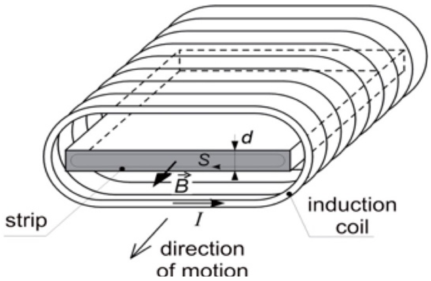

Fig. 1: Principle of longitudinal flux heating

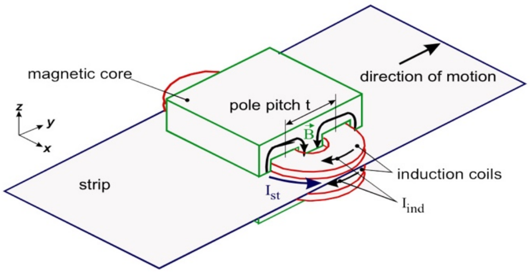

Fig. 2: Principle of transverse flux heating

For nearly flat materials with constant cross-section the longitudinal induction heating concept can be applied, ensuring a homogenous temperature profile. Unfortunately, the application range is limited. If the needed temperature of steel material is above the Curie point (around 760 °C depending on the material), the minimal material thickness which can be heated sufficiently is limited to approximately 1 mm. This is caused by maximum achievable heating frequencies of the power supplies which are below 1 MHz.

Transverse flux heating

The principle of transverse flux heating (TFH) is shown in Fig. 2. The material to be heated is positioned between two inductors located above and below the strip. The electromagnetic field created by a certain frequency current in the induction coils is mainly oriented orthogonally to the material surface. Due to the direction of the field, eddy currents are induced in the plane of the strip and produce Joule heat in the strip. Depending on particular requirements, TFH installations can be accomplished by magnetic flux guiding elements. By an appropriate design of the induction coil it is possible to influence the currents in the strip and herewith the temperature for a concerted non-uniform heating. This opportunity of influencing the temperature distribution is not given by longitudinal flux heating. However, to reach homogeneous temperature profiles with transverse flux heating, the system has to be accurately designed.

Transverse flux heating has advantages even against the induction longitudinal heating principle. On one hand this is indicated by working conditions such as two decades lower frequency, higher efficiency and the induction coils which do not enclose the heated strip.

Comparison of both induction heating concepts for the use in hot metal forming

For hot metal forming where the work-pieces typically are blanks and not strips both induction methods feature advantages in energy consumption and in the ability of achieving inhomogeneous temperatures. But the task to get finally a homogeneous temperature distribution on a high temperature level is difficult for transverse induction heating, therefore, longitudinal flux heating is the preferable concept.

Induction heating is not predestined for the task of temperature holding, which can be required e.g. for metallurgical aspects. It is rather a method for fast heating up. Conventional furnaces with adapted radiation temperature are more effective to realize holding and equalization.

Furthermore, holes or notches in the sheets are in general a problem for induction heating, because the induced current in the material will be concentrated at borders of holes. This can lead to local overheating at the borders. This fact has to be considered by the design of the induction heating process.

Currently a lot of investigations are carried out for the optimal heating process for hot forming of metal blanks in automotive industry.

Fig. 3 illustrates four possible concepts to heat a pre-shaped sheet or endless strip [5]. The concepts are shortly described in the following.

For thin moving sheets longitudinal flux heating can be used as a booster till Curie temperature (Fig. 3-1). The final temperature above 760 °C is reached by conventional heating such as hot air or radiation heating. In batch mode (the work-piece is placed without movement in the heating stations) it is also possible to heat thin sheets by longitudinal flux heating (Fig. 3-2). But higher temperatures need also an additional conventional heating. The design of the heater must be adapted for each work-piece. Changes in the cross-section can be considered by progressive coil design. This concept can be reasonable for small production lots. Transverse flux heating is beneficial for endless strip. Therefore, a concept could be the heating of endless strip from ambient to final temperature by transverse flux heating with very good efficiency (Fig. 3-3). High flexibility can be reached using several small transverse flux heaters with separate power control (Fig. 3-

4). Depending on the work-piece an optimal selection of heaters and individual power is chosen. But it has very high requirements on the design.

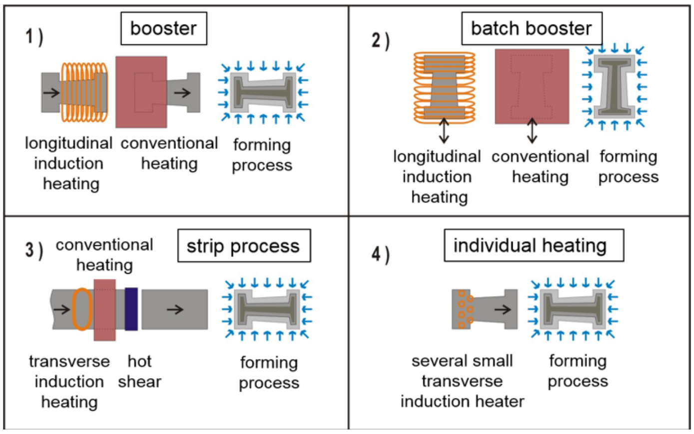

Fig. 3: Heating concepts for hot forming of high strength steel: 1) combined longitudinal flux heating and conventional furnace for continuous mode; 2) batch mode of the combined process; 3) transverse flux heating of endless strip with hot shear; 4) heating by a combination of several small heaters

Investigation of a single-stage induction heating concept regarding discontinuities in the blanks

In the frame of a research project funded by the German Government an induction heating system was investigated which allows a single-stage induction heating up to temperatures of 950 °C. Detailed studies are described in [6-8]. In this paper the most important results are summarized.

The advantage of single-stage induction heating is that it can work without conventional heating systems and, therefore, is most energy effective. In the hot metal forming process, the blanks are typically heated up to a temperature between 930 °C and 950 °C for AlSi coated and uncoated material in order to reach the austenitization temperature.

The blanks typically have irregular forms. Irregularities are holes, cut-outs or changes in the cross-section. In this investigation particularly holes are taken into account and the electromagnetic and thermal behavior due to these irregularities are shown. Furthermore, different geometrical parameters of the system of the induction coil and the work-piece are investigated and from this investigation design rules for the induction coil are derived.

The investigations are mainly carried out by numerical simulations followed by experimental tests for verification of the numerical results.

The numerical model

For the calculation of the following results a 3-dimensional FEM model is used. The material properties such as specific electrical conductivity, relative permeability, specific thermal conductivity and specific heat capacity are adjusted to the transient temperature distribution. Because of symmetry only one half of the system is modeled in order to reduce the calculation time. A sketch of the investigated heating system is shown in Fig. 4. The induction coil has a rectangle cross-section. For an exact calculation it is important to mesh the edges of the blank very fine. The calculations are based on the material properties of 22MnB5 steel [2]. The reference thickness of the blank is 1,5 mm, because in many industrial applications blanks with a thickness in this range are used. The width of the blank is 200 mm. The width of one winding is 30 mm and the distance between the windings is 10 mm. The coil has 8 parallel windings. The frequency of the current is 400 kHz. The simulation results are verified by experimental investigations which are described in detail in [8].

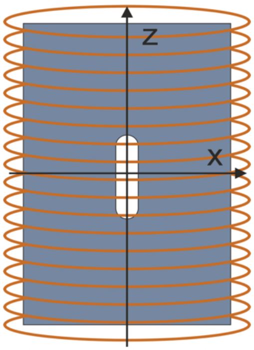

Fig. 4: Sketch of the induction heating system

Numerical investigation of the influence of holes

The following results show some main results of the study carried out in the research project. Detailed results are described in [6-8]. In this paper only the principal effect of a hole on the electromagnetic field, the Joule heat distribution and the temperature distribution during longitudinal flux heating is described.

In the simulation the blank is located in the coil during the heating process (batch heating). The current in the induction coil is applied with a frequency of 400 kHz and an amplitude of 960 A. The heating process takes 20 s and ends with a temperature of around 950 °C.

The position of the hole is normal to the induction coil. The center of the hole is located at the x-coordinate 0 mm and the z-coordinate 0 mm. The hole has a width of 14 mm and a length of 96 mm. The radius of the corner is 3.5 mm.

Fig. 5 shows the Joule heat distribution in the blank close to the hole. The strip pattern is caused by the coil. Because of higher magnetic field intensity under the windings a higher current is induced and hence higher Joule heat is generated.

At the long sides of the hole less Joule heat is generated. This is understandable with a look at Fig. 6. The current doesn't flow parallel to the edge of the hole rather it turns around and flows back on the backside of the blank. The generated Joule heat results in a temperature distribution close to the hole (Fig. 7). The strips produced by the windings are noticeable and the attracted magnetic field causes a little higher temperature at the small endings. Due to this main results, the influence of holes and cut-outs are much less than expected before. But these influences are only low if the used frequency is high enough in order to generate a pronounced skin effect over the blank thickness which is necessary for pure longitudinal flux heating. If the skin effect is less pronounced currents will close in other ways, than only from top to down side of the blank. In this case local overheating close to the hole can occur.

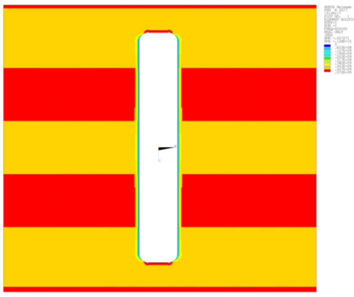

Fig. 5: Joule heat distribution close to the hole

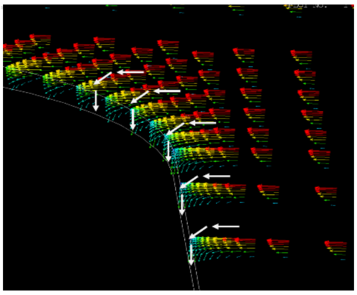

Fig. 6: Current flow at the hole

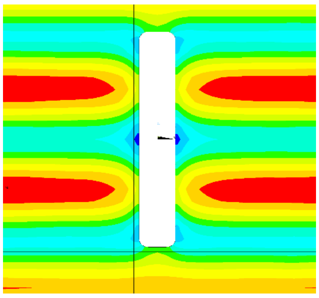

Fig. 7: Temperature distribution close to the hole

Conclusions

Induction heating is an effective heating method which allows a high energy efficient heating in many applications. The biggest advantage is the high heating speed and the high thermal efficiency if a fast heating is required. Induction heating is less suitable for holding processes. Therefore, in the case of necessary holding processes hybrid heating of a combined induction and conventional furnace heating can offer many advantages regarding energy efficiency and product quality.

For hot metal forming of car body parts, a comprehensive study for a single-stage induction heating process has been carried out. The influence of discontinuities such as holes, cut-outs and changes in cross-section has been investigated in detail by numerical simulations and verification by experiments.

One important result of the investigation is that in the case of longitudinal flux heating typically at the edge of holes a lower temperature exists in contrast to the general estimation, that holes generates temperature overheating at their edges. The lower temperature at the edges of holes is caused by the fact that the current close to a larger hole cannot cross the hole and tends to flow back on the down side of the blank. This is due to the general principle of longitudinal flux heating that currents are closing in the cross-section of a blank or strip.

Acknowledgment

The research project "Series-production of inductively heated blanks for hot sheet metal forming" (IFG-No. 18738 N) from the Research Association for steel Application (FOSTA) and the Research Association of Automotive Technology (FAT) is supported by the Federal Ministry of Economic Affairs and Energy through the German Federation of Industrial Research Associations (AiF) as part of the programme for promoting industrial cooperative research (IGF) on the basis of a decision by the German Bundestag.

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