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Residual stress analysis of laser spot welding of steel sheets

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ABSTRACT

Experimental and numerical studies were conducted to characterize laser and resistance spot welds to gain an understanding of load carrying capacity, temperature distributions and residual stress states of different joint geometries used in the automotive industry. Different laser spot weld path geometries are compared with conventional resistance spot welds to find the residual stress distributions in each. It was found out that the weld region in laser spot welding is surrounded by a compressive region which has higher compressive stress values and larger size than that of resistance spot welds. Simulations showed good agreement with experimental temperature distributions, and were able to qualitatively predict the residual stress distributions in each of the weld geometries. The thermal history at known failure locations within the welds and the influence of the weld geometries on cooling rate are also discussed.

1. Introduction

Resistance spot welding (RSW) remains the most widely-used joining method in the automotive industry [1]. However, laser spot welding (LSW) provides a flexible alternative to RSW with the benefits of low distortion due to concentrated heat source, and requires only line-of-sight (with one side of the area to be welded) fabrication, allowing for access to more difficult-to-reach areas. Further advances, such as the remote welding method [2], will allow even higher rates of throughout, which is of great importance when considering the high volumes and quantities of welds associated with automobile manufacture.

Simulation of welding processes has its roots in the first analytical welding models proposed by Rosenthal [3], which approximated the heat source as a single point or line through the material. Over time, models with a distributed heat source across a surface [4] and throughout a 3D volume [5] were developed, making the accurate modelling of a range of different heat sources, including laser beam welding (LBW), possible. Mazumder and Steen [6] proposed a FE-method with specific considerations for the keyhole mode of laser welding, and work in understanding and simulating the physical phenomena found within the fusion zone was continued by Sudnik et al. [7]. Significant increases in computational power in the last two decades have made finite element analysis using 2D and 3D meshes possible, as well as the prediction of residual stresses in and around the welded region. Recent simulations using commercial software such as ABAQUS [8,9], ANSYS [10], and the more function-specific SYSWELD [11,12] have all been successful in determining residual stresses, both for LBW and other welding processes.

Improved understanding of the fatigue behaviour, in connection with residual stresses, is an extremely important subject particularly for newly developed welding processes such as LSW. Previous work [13] has compared the fatigue behaviour of resistance spot welds and laser spot welds of dissimilar materials, including advanced high-strength steels (AHSS), while others have analysed different types of butt-welded specimens on a microstructural level [14]. Thermo-mechanical analysis of laser spot welding can provide useful information to improve the understanding of the cyclic behaviour of welded structures, and this information can lead to better damage-tolerant design of these structures. The present paper aims to determine the effect of different laser spot weld shapes on the residual stress state in comparison with the residual stress state found in resistance spot welds, primarily through an analysis of the residual stresses developed. Simulation of the LSW process using the ABAQUS FE suite was conducted alongside the experimental analysis, and comparisons of results will be presented. Fatigue performance of the different laser spot weld path geometries will be reported in the next communication due to the space available in this manuscript.

2. Experimental procedure

Although the term laser spot welding is used, welding occurs over a short continuous path, rather than at a single point, which is the case for resistance spot welds. This terminology was chosen

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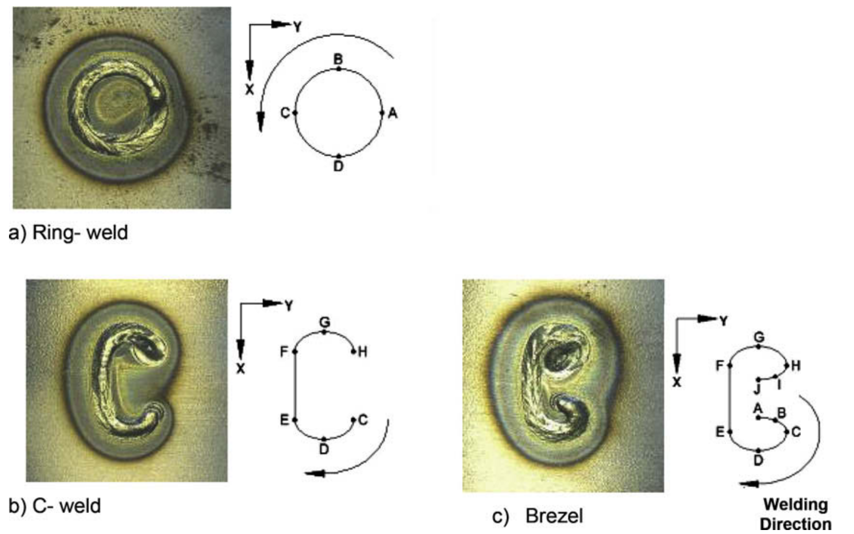

Fig. 1. Laser spot welds and schematics showing welding direction and configurations used in this study.

to draw comparisons with RSW, which the LSW process was developed to produce welds of similar quality, while maintaining the same or possibly shorter cycle times. The variation of these paths, using different combinations of lines and circular or elliptical arcs, led to the development of the four weld geometries that were analysed.

2.1. Welding path geometries

The "Ring weld" geometry of LSW and the nugget type of RSW were taken from our prior work [13], and would be used as the basis for comparison with other geometries. The start point of laser welds is often prone to failure due to low penetration and high cooling rate while the end point is often prone to failure due to impurities pileup as a result of keyhole collapse. The "Ring" configuration mitigates the lack of penetration at the start point through overlap with the end point, which has full penetration. However, the issue of poor weld quality caused by keyhole collapse was not addressed, and so a new geometry was developed, where both the start and end points were protected from external forces by a layer of continuous welded material. This geometry was simply referred to as "Brezel" (see Fig. 1). This weld geometry can also be used to reduce the edge size of profiles used in automobile body-in-white, and lead to weight savings. Lastly, to determine the effect of the so-called "protected endpoints" on fatigue behaviour, a third sample possessing the same geometry as the Brezel, without the first and last sections, was also used, and this was referred to as a "C- weld" (see Fig. 1). Dimensions were chosen to create Brezel welds with a short to long axis ratio of 0.5, and ensure that proper spacing was given on all sides of the start and end points. The final Brezel welds had a length of 11 mm and a width of 6 mm. The radius of Ring welds was selected such that the weld seam length was equivalent to the Brezel welds, and a radius of 4.5 mm was used.

2.2. Welding process and specimen preparation

All laser welds were made using a 3.3 kW Nd:YAG laser without shielding gas or filler wire at the GKSS facilities, and further welding parameters of 11 mm s^{-1} welding speed, +8.0 mm focal point, without shielding gas and filler wire were adjusted to obtain optimum joints, as judged by visual examination of the weld nugget surface appearance and sufficient weld penetration in the lower sheet of the overlap joints. 2.0 mm sheet thickness deep-drawn DC04 steel was chosen as the material on which all welds would be made, due to its prevalent use in the automotive industry. All welds were made on overlap specimens with dimensions given in Fig. 2. All geometries were centred in the middle of the 40 mm by 40 mm single overlap section of the specimen.

The resistance spot welds were made using a Schlatter 50 HZ AC stand alone spot welding machine at OCAS. Spot welds were made with a nugget diameter of approximately 7.0 mm (i.e. $5\sqrt{t}$) in the centre of a 40 mm overlap between the sheets and with 42 mm between spots. The welded panels (1000 mm × 300 mm) were then cut to tensile–shear (TS) coupons. A typical joint cross section of a resistance spot weld is shown in Fig. 3a.

2.3. Test methodology

In order to evaluate temperature distributions of the different geometries, five thermocouples of type K with 0.5 mm diameter were placed around the weld paths, with four in the top sheet and one in the bottom sheet. Temperature values were recorded at 200 Hz and were used for comparison with simulations. A high speed video system was used to gain information about the length of the melt pool and the keyhole diameter, which was also used in the simulations. The videos were recorded at 1000 frames per second (fps).

Residual stress measurements using neutron diffraction were conducted on laser and resistance spot welded specimens. These were made along the major axes of the specimens, as shown in Figs. 2 and 3. Comprehensive descriptions of the method of residual stress analysis by diffraction can be found in the textbooks by

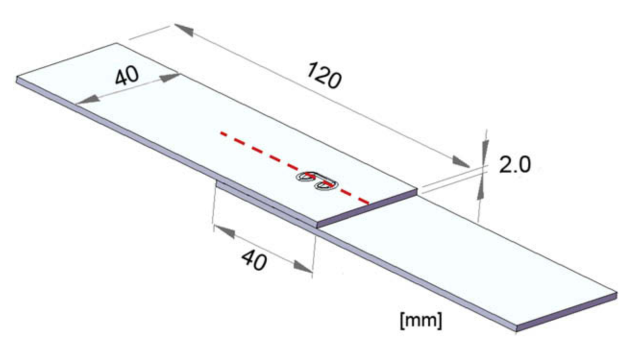

Fig. 2. Geometry and dimensions of laser spot welded specimens; residual stresses were measured along the dashed line.