Appl. Phys. A 74 [Suppl.], S1440–S1442 (2002) / Digital Object Identifier (DOI) 10.1007/s003390201431

Applied Physics A
Materials
Science & Processing

Residual stress in clinched joints of metals

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Received: 17 July 2001/Accepted: 8 January 2002 –

Abstract. Diffraction methods are used for the determination of characteristic residual stress (RS) distributions in undismantled clinched samples for the assessment of the influence of RS on the mechanical behaviour of clinched joints. While X-ray diffraction enables merely the determination of near-surface RS distributions, the higher penetration depth of neutron radiation allows the determination of triaxial RS states inside the material. In addition, the complex geometry of clinched joints restricts the application of X-ray RS analysis. Therefore a combined RS determination by X-ray and neutron diffraction has been used to obtain an expressive assessment of the RS distributions in the immediate vicinity of clinched joints. Two different materials with different mechanical behaviour were used for clinching, as well as two different common clinching techniques.

PACS: 81.85.Hf; 081.20.Vj; 81.70.Bt

Clinching is a mechanical press-joining method based on local cold forming to unite two or more metal sheets by forming a form and force locking joint without the need of auxiliary material. Although clinching has been known for more than 100 years [1], only in recent years can increased industrial interest in clinching be noticed since the technique was successfully applied to complement or even replace other joining techniques such as, for example, spot welding [2]. Its potential to find extensive applications as an alternative joining technique is based not least on its low costs, its flexibility and its environmental compatibility. There still exists a lack of knowledge concerning the mechanical behaviour of clinched joints under quasistatic and cyclic loading. The apparent low mechanical strength of clinched joints (resistance to shear or tensile loading) compared to equivalent spot-size spot welds limits their applications to parts with low requirements for the mechanical strength [3]. Investigations of the mechanical behaviour under dynamic loading yielded that the clinched joints partly had a longer lifetime expectancy than spot-welded joints [2, 4]. In particular, the RS induced by the severe cold forming during joining in the vicinity of clinched joints has not been of specific interest yet, although it may affect the mechanical behaviour of the joint structure, especially when considering overlapping stress fields from neighbouring clinches. Here we take the first step to attack this problem by characterising the RS distribution in the vicinity of a single joint for two different materials and two different clinching techniques. The RS is measured by both neutron and X-ray diffraction.

1 Experimental procedure

Two materials with different mechanical behaviour were used for clinching, a microalloyed steel ZStE340 (sheet thickness $t = 2$ mm) and a non-age-hardenable aluminium base alloy AlMg5 ($t = 1.5$ mm, Table 1). Two different axisymmetric single-stage non-cutting clinching techniques were applied: the TOX [5] and the Eckold techniques [6]. The Eckold method uses a two-segmented die to form the clinch lock, whereas for the TOX joining process a non-split die is used. In the case of the TOX clinch, material flows into a ring groove in the tool die and forms a so-called clinch lock by mutual insertion of the metal sheets. For the Eckold technique the clinch lock is created by the extensible die which opens during the clinching process and permits an additional material flow in the radial direction. This results in a non-rotationally symmetric design of the Eckold clinch. For this reason the RS was determined on two paths (see Fig. 1). The two different clinching processes result in a distinct diverging appearance of the clinch geometry. The micrographs showing cross sections through the steel clinches (Fig. 2) clearly

Table 1. Mechanical properties of the non-clinched materials

	ZStE340	AlMg5
0.2% yield strength [MPa]	363	131
Tensile strength [MPa]	467	265
Elongation [%]	25.8 (A_{80})	23 (A_{50})

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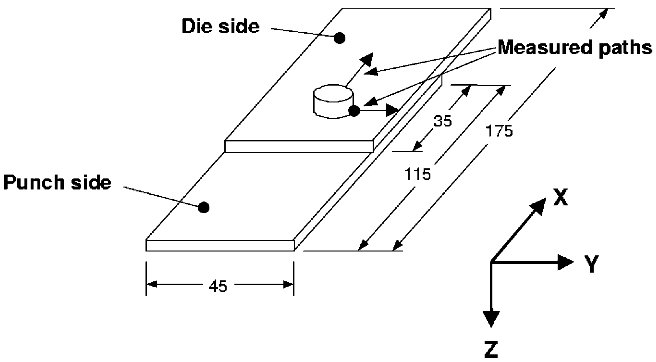

Fig. 1. Geometry of the sample co-ordinate system used

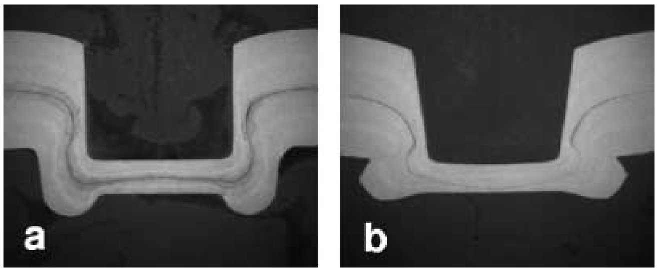

Fig. 2a,b. Cross sections through the TOX **a** and the Eckold **b** steel clinches

illustrate the different material flow during the clinching process. Contrary to the TOX clinch, the Eckold clinch develops a larger clinch lock.

Triaxial neutron strain scanning has been performed on the REST facility of Studsvik Neutron Research Laboratory. Measurements were carried out in the half-sheet thicknesses of the upper (punch side) and the down sheets (die side) for different distances from the outer clinch diameter. In addition, three measurement points are situated directly in the clinch as illustrated by the sketch in Fig. 3. For the strain measurements the {311} lattice planes of the *fcc* aluminium base alloy ($2\theta = 93.76°$) and the {211} planes of the *bcc* ferrite of the steel ($2\theta = 88.3°$) were used. Due to measurement-time optimisation, different gauge volumes were used for the different measuring directions. The determined elastic strains were converted into RS by the use of Hooke's law with $E_{\mathrm{Al}}^{\{311\}} = 90\,\mathrm{GPa}$, $\nu_{\mathrm{Al}}^{\{311\}} = 0.35$ and $E_{\alpha-\mathrm{Fe}}^{\{211\}} = 22\,\mathrm{GPa}$, $\nu_{\alpha-\mathrm{Fe}}^{\{211\}} = 0.28$, respectively [7].

Complementary X-ray RS analyses were carried out on a Seifert XRD 3000 PTS using CuKα radiation, which yields a very small penetration depth for steel. The measurements were carried out at the same paths as for the strain scanning by neutron diffraction. The primary beam was limited by a 1-mm pinhole collimator; a secondary slit of 1 mm was used in front of the counter. Strain measurements were performed for the {422} lattice planes of the aluminium base alloy and the {222} planes of the ferrite phase. For the RS calculation the $\sin^2\psi$ technique [8] was applied by using $E_{\mathrm{Al}}^{\{422\}} = 71\,\mathrm{GPa}$, $\nu_{\mathrm{Al}}^{\{422\}} = 0.35$ and $E_{\alpha-\mathrm{Fe}}^{\{222\}} = 248\,\mathrm{GPa}$, $\nu_{\alpha-\mathrm{Fe}}^{\{222\}} = 0.28$ [7].

2 Results and discussion

In Fig. 3 the RS components determined by neutron diffraction inside the steel clinches are exemplarily presented. Qualitatively, the same tendency can be observed for the radial

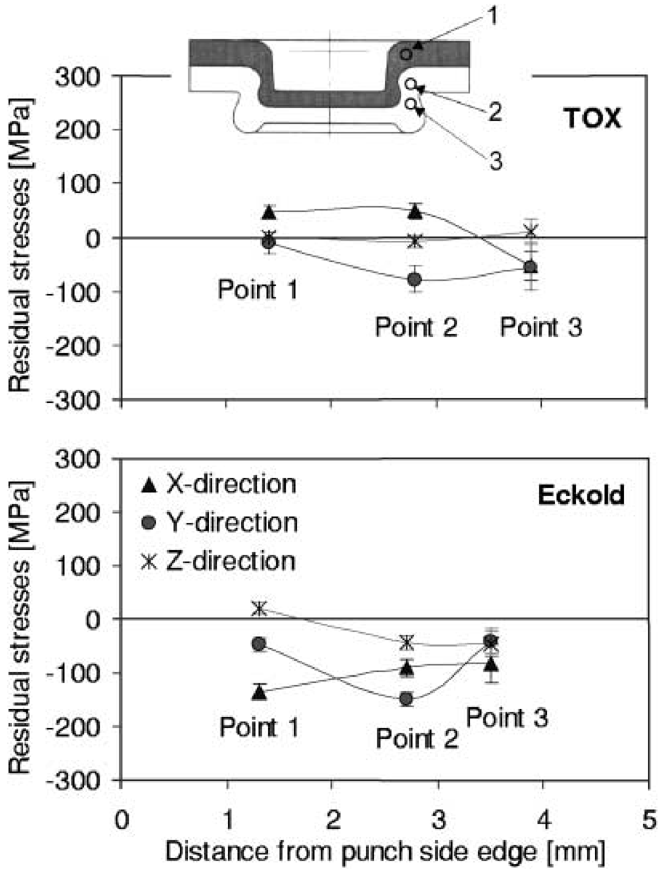

Fig. 3. RS values inside the steel joints, X = hoop, Y = radial, Z = axial (*up*: TOX, *down*: Eckold)

direction (Y). Here the highest compressive RS occur in point 2. Almost similar joining forces during processing result in slightly lower compressive RS in the case of the TOX clinch. In the axial direction (Z) both clinching techniques show almost zero RS within the range of the measurement uncertainty. For the hoop direction the determined RS distributions for both techniques differ clearly. Near the punch-side edge (point 1) and in the region of the minimum upper-sheet thickness (point 2) – where normally fracture during shear–tensile tests occurs – for the TOX clinch low tensile RS were determined; the Eckold technique induces compressive RS. Near the bottom of the clinch (point 3) small amounts of RS in the hoop direction were detected.

FWHM values of the respective interference profiles measured by neutron diffraction are presented in Fig. 4. A similar behaviour was observed for both clinching techniques. The interference line width increases slightly from the punch-side edge (point 1) to the die-side edge (point 3). Therefore, for the irradiated gauge volumes, the highest amounts of plastic deformation might occur in the clinch-lock region.

Data obtained by both X-ray and neutron diffraction in the hoop direction of the Eckold clinch are shown in Fig. 5. Despite the non-rotationally symmetric design of the Eckold clinch, nearly the same RS distribution for the hoop component is determined by neutron diffraction in both directions X and Y. This might be the averaging effect of the large measurement volumes during the neutron-diffraction experiments. The more locally resolved X-ray-diffraction data reveal dif-

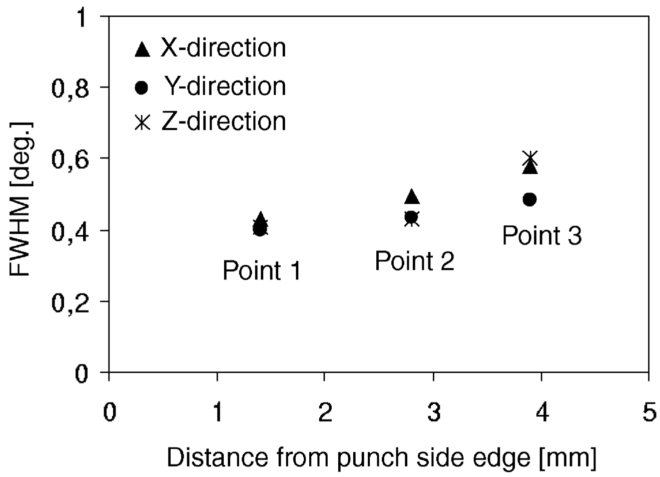

Fig. 4. FWHM inside the TOX steel clinch joints

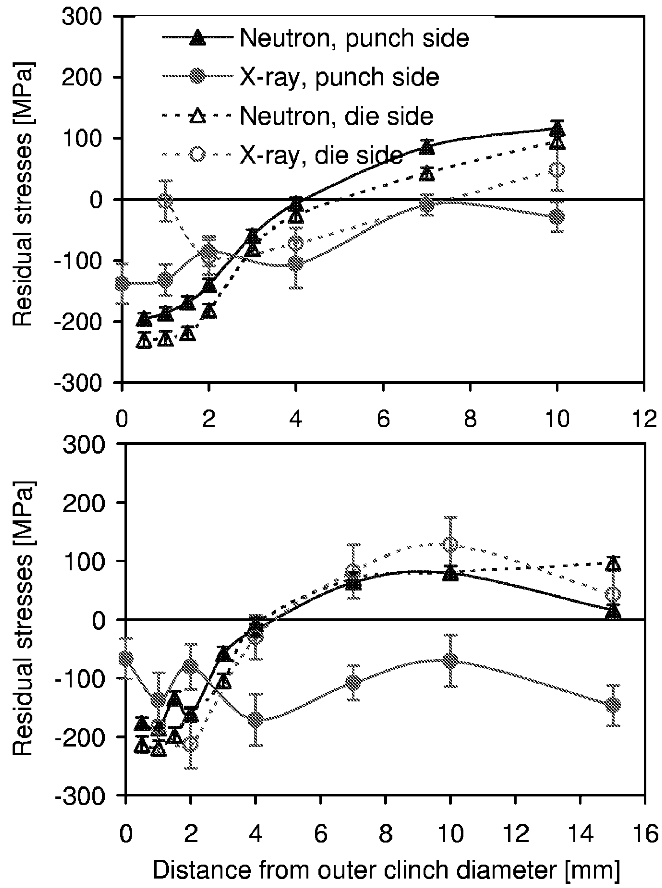

Fig. 5. RS distributions of the Eckold steel clinch (hoop stress, *up*: path in X, *down*: path in Y)

ferences in the determined near-surface RS distributions in the load direction and transverse to it. For larger distances to the outer clinch diameter (> 2 mm) the hoop RS in the load direction shows good agreement on both sides of the sheets, whereas on the path in the Y direction the RS distributions are strongly diverging on the die and the punch sides. These distinctly different RS distributions with respect to the orientation of the Eckold clinch may affect the mechanical behaviour of the clinch under load. For the TOX process the RS field around the clinch is rotationally symmetric. In the immediate vicinity of the TOX clinch compressive RS were also determined, but the magnitudes of the respective RS distributions are distinctly lower than for the Eckold clinches.

The results determined for the steel samples can essentially be transferred to the aluminium base alloy. Qualitatively similar RS tendencies were determined, but the effects are less pronounced due to the distinctly lower strength of the AlMg5. It has to be kept in mind that for the steel clinches measurements were only carried out in the ferrite phase.

3 Conclusions

Characteristic RS distributions were found for the combinations of clinching technique and joined sheet material investigated here. It has been derived that the clinching process induces predominantly compressive RS inside the clinch and in the immediate vicinity of the clinch. With increasing distance to the clinch the compressive RS were generally balanced by tensile RS.

In the case of the Eckold clinch different near-surface RS distributions are determined in the direction of the split plane and in the perpendicular direction. The region under compressive RS extends to about 4 mm outside the clinch diameter. For the TOX clinch the symmetric compressive hoop stress extends up to 6 mm outside the clinch diameter.

Acknowledgements. Access to facilities at the Studsvik Neutron Research Laboratory has been supported by the Access to Research Infrastructures activity, Improving Human Potential programme, of the European Commission under Contract No. HPRI-CT-1999-00061. The authors wish to thank N. Dölle and C. Dye from LWF, University of Paderborn for providing the clinched specimens.

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