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DISTORTION-FREE WELDING OF THIN-WALLED ELEMENTS BASED ON THERMAL TENSIONING EFFECTS[1]

Buckling distortions are more marked than other forms of welding distortions in manufacturing thin-walled structural elements. They are the main troublesome problems in sheet metal fabrication where fusion welding is applied especially for aerospace structures such as sheet metal formed airframe panels, fuel tanks, shells of jet engine cases etc. with material thickness less than 4 mm. Extensive research and development studies to explore distortion-free welding techniques were carried out at Beijing Aeronautical Manufacturing Technology Research Institute (BAMTRI).

To prevent buckling, Low Stress No Distortion (LSND) welding techniques were pioneered at BAMTRI and implemented successfully for product engineering and component manufacturing. Two innovative methods of LSND welding techniques have been developed for industrial application: one is based on the whole cross-section thermal tensioning effect, the other is based on the localized thermal tensioning effect.

The nature of LSND welding techniques is to create active in-process control of incompatible (inherent) plastic strains and stresses formation during welding to achieve distortion-free results implying that no post weld costly reworking operations for distortion correction is required. In this paper, the mechanisms of LSND welding techniques either using whole cross-section thermal tensioning effect or using localized thermal tensioning effect are described and analyzed in details.

Introduction. Buckling distortions affect the performance of welded structures in a great many ways. During the past decades efforts have been made and progress has been achieved in solving buckling problems by experts in the welding science and technology field world-wide. Many effective methods for removal, mitigation and prevention of buckling distortions adopted before welding, during welding or after welding have been successfully developed and widely applied in industries (Refs. 1–7). Over the past 25 years, the present author and his team have devoted their efforts to achieve distortion-free results in manufacturing thin-walled aerospace structural components by implementing active in-process control of inherent residual plastic strain formation during welding without having to undertake costly reworking operations for distortion correction after welding (Refs. 8–10). Two innovative methods of LSND welding

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techniques have been developed for industrial application: one is based on the whole cross-section thermal tensioning effect (Ref. 9), the other is based on the localized thermal tensioning effect (Ref. 10).

The nature of buckling is mostly a phenomenon of loss of stability of thin elements under compressive stresses. Buckling distortions caused by longitudinal welds either in plates, panels or in shells are mainly dominated by longitudinal compressive residual stresses induced in areas away from the weld. The mechanism of buckling in weldments lies in the action of inherent residual plastic (incompatible) strains formed during welding.

Losing stability, the buckled plate is released from an unstable flat position of high potential energy with the maximum level of residual stress distribution after conventional welding and takes a stable warped shape. Losing stability, the buckled plate reaches a state of minimum potential energy . In other words, any forced change of the stable curvature of the buckled plate will cause increase in potential energy and once the force is removed, the buckled plate will be restored to its stable position minimizing the potential energy.

For plates of thickness less than 4 mm as widely used in aerospace and modern vehicle welded structures, the value of σ_{cr} at which buckling occurs is much lower than the peak value of residual compressive stress $\sigma_{comp\text{-}max}$ after conventional gas tungsten arc welding (GTAW). However, the actual value σ_{cr} for a welded element is difficult to be solely determined either by the linear stability theory of small deformations or by the non-linear theory of large deformations in theory of plates and shells.

In principle, all efforts either “passive” post-weld correction measures or ’active’ in-process control methods of Low Stress No-Distortion (LSND) welding to eliminating buckling aim at adjusting the compressive residual stresses to achieve $\sigma_{comp\text{-}max} < \sigma_{cr}$ by means of reduction and redistribution of the inherent residual plastic strains.

Buckling can be controlled by a variety of methods applied before welding, during welding and after welding for its removal, mitigation or prevention.

Low Stress No-Distortion (LSND) results could be achieved during the welding process based on the thermal tensioning (temperature gradient stretching) effect which is produced by establishing a specific temperature gradient either in whole cross section of the plate to be welded or in a localized area in the near-arc zone. Simultaneously, restraining transient out-of-plane warpage movements of the workpiece is necessary. Differing from the ’passive’ methods which have to be applied after welding once buckling is in existence, LSND welding techniques can be classified as ’active’ methods for in-process control of buckling distortions with no need of reworking operations after welding (Refs. 8–10).

Thermal Tensioning Effects. The basic principle of the whole cross-section thermal tensioning effect is shown in Fig. 1. Two curves (σ_{x1} and σ_{x2}) of thermal stress distributions are created by a preset heating with the temperature profiles (T_1 and T_2) correspondingly on the thin plate. In this case, the thermal tensioning effect is defined as the value of σ_x^* in the plate edge of $Y = 0$ where the weld bead will be applied. For a given σ_x^*, the greater temperature gradient $\left(\dfrac{\partial T_1}{\partial Y} > \dfrac{\partial T_2}{\partial Y}\right)$, the higher will be the induced maximum value of compressive stress $-\sigma_{1x_{max}}$. An optimized temperature curve can be calculated mathematically for an estimated value σ_x^* while the value $-\sigma_{x_{max}}$ is kept below the yield stress.

As an active in-process control method, thermal tensioning techniques have been improved at BAMTRI and is more widely acknowledged as Low Stress No-Distortion (LSND) welding methods for thin materials (Refs. 9, 10). It is worthwhile to note, that the LSND welding techniques as active in-process control methods are replacing the formerly adopted passive measures for buckling removal after welding in most cases in aerospace engineering in China.

The thermal tensioning effects can be classified into two categories: one is created in an whole cross-section of plate (whole cross-section thermal tensioning) using additional heating and cooling as mentioned above, the other is created in a localized zone limited to a near arc high temperature area within a certain isotherm induced solely by welding arc without any additional heating (localized thermal tensioning). For the localized thermal

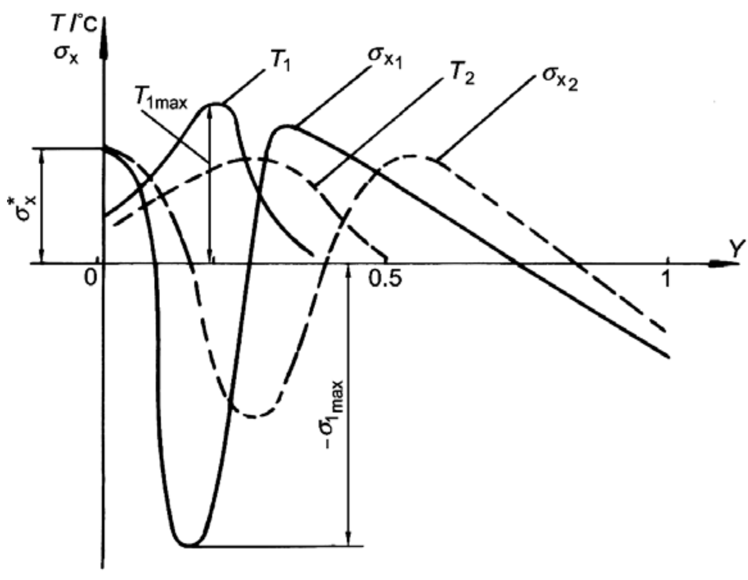

Fig. 1. Basic principle of whole cross-section thermal tensioning effect

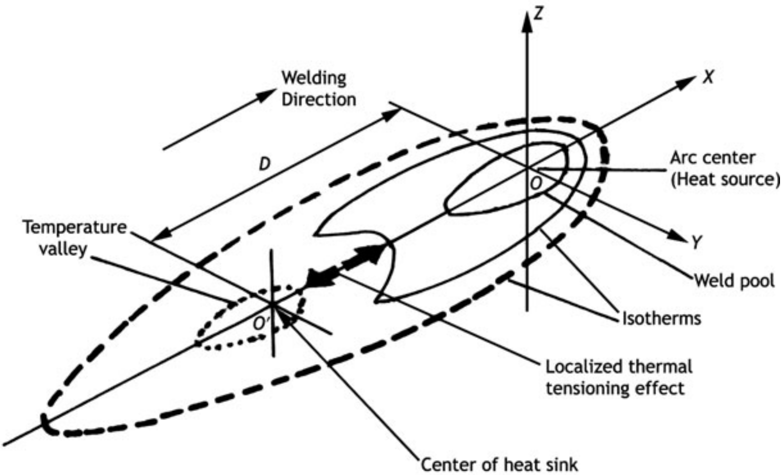

Fig. 2. Localized thermal tensioning effect (shown by heavy arrows) induced by a trailing spot heat sink coupled to the welding arc in a distance D behind

tensioning a heat source-heat sink system — a heat sink coupled with welding heat source, could be utilized (Fig. 2).

Whole Cross-Section Thermal Tensioning — LSND Welding. To satisfy the stringent geometrical integrity requirements and ensure dimensionally consistent fabrication of aerospace structures, Low Stress No-Distortion (LSND) welding technique for thin materials, mainly for metal sheets of less than 4 mm thickness, was pioneered and developed early in 1980's at the Beijing Aeronautical Manufacturing Technology Research Institute (Refs. 8, 9). This technique was aimed to provide an in-process active control method to avoid buckling distortions based on the whole cross-section thermal tensioning effect. It is proved by experiments and engineering applications, that the thermal tensioning effect is the necessary condition for LSND welding of materials of less than 4 mm thickness, whereas the sufficient condition is the prevention of transient out-of-plane displacements by applying flattening forces.

The typical temperature field in GTA welding of thin plate is shown schematically in Fig. 3, a. Actually, in engineering practice, the GTAW of longitudinal weld on thin plate is performed in a longitudinal seam welder. Workpieces are rigidly fixed in a pneumatic finger-clamping system with copper backing bar on mandrel support. Owing to the intensive heat transfer from workpiece to copper backing bar, the temperature field is different from the normal shape and takes a narrowed distribution as shown in Fig. 3, b. To implement LSND welding, additional preset temperature field as shown in Fig. 3, c is formed by heating and cooling, Therefore, the LSND welding temperature field shown in Fig. 3, d results by superposition of the temperature fields of Fig. 3, b and c.

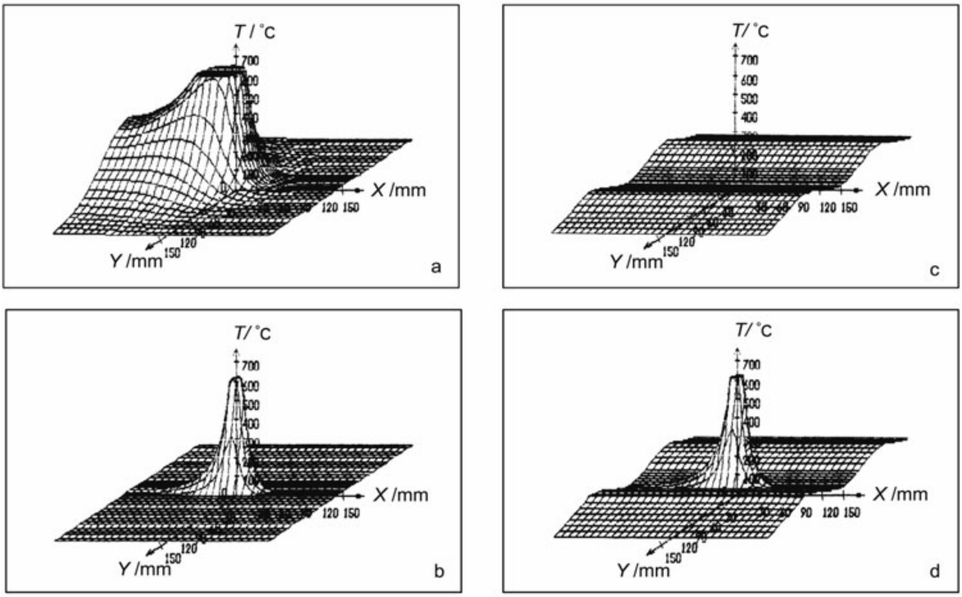

Fig. 3. Temperature fields on thin plate of conventional GTAW (a), GTAW on copper backing bar with intensive heat transfer (b), preset temperature field (c) and temperature field for LSND welding (d)

For clearer quantitative assessment of LSND welding technique, a systematic investigation was carried out (Refs. 8, 11). Fig. 4 shows comparisons between the experimentally measured inherent strain $\varepsilon_{\mathrm{x}}^{\mathrm{p}}$ distributions (Fig. 4, a) and residual stress σ_{x} distributions (Fig. 4, b) after conventional GTAW (curve 1) and LSND welding (curve 2) of aluminum plate of 1.5 mm thick. Reductions of either $\varepsilon_{\mathrm{x}}^{\mathrm{p}}$ or σ_{x} are obvious (as indicated by curve 2 in comparison with curve 1).

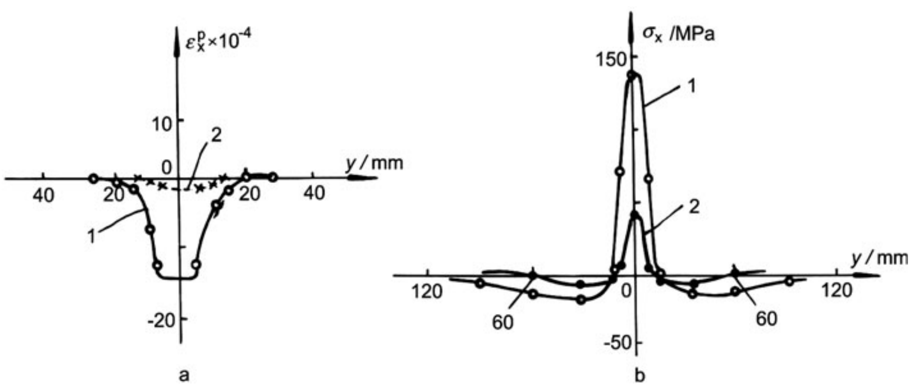

Fig. 4. Comparisons between experimentally measured inherent strains ε_x^p (a) and residual stresses σ_x (b) distributions after conventional GTAW (curve 1) and LSND welding (curve 2) of aluminum plate of 1.5 mm thick (Refs. 8, 11)

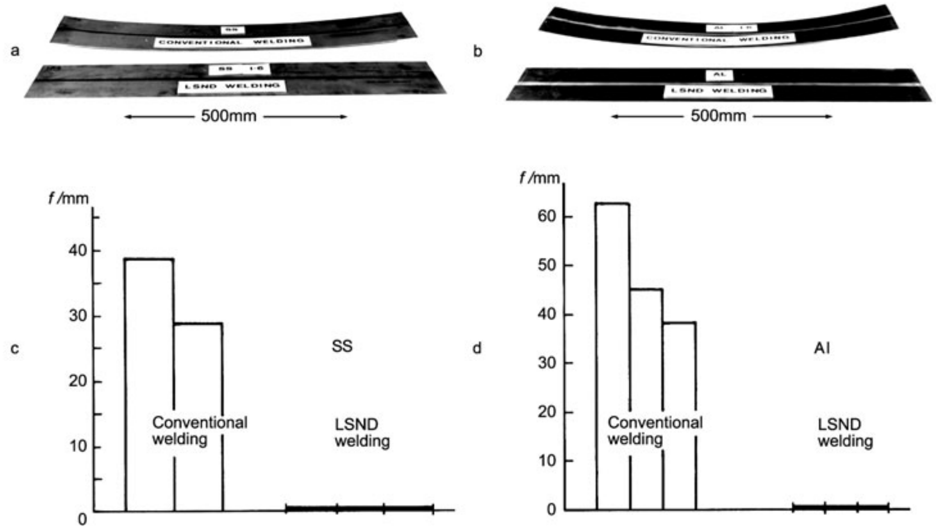

Fig. 5. Specimens of 1.6 mm thick, 1000 mm long, of stainless steel (a) and aluminum alloy (b) welded by conventional GTAW, severely buckled (upper), and welded by LSND welding, buckle-free (lower). Completely buckle-free results ($f = 0$) can be achieved using optimized LSND welding technique on both stainless steel (c) and aluminum alloy (d) specimens of 1.6 mm thick (Ref. 11)

The photographs in Fig. 5 show that the specimens of either stainless steel (Fig. 5, a) or aluminum alloy (Fig. 5, b) welded conventionally (upper photo) are severely buckled in all cases. But the specimens welded by use of LSND welding (lower photo) are completely buckle-free and as flat as before welding.

Comparisons are also given in Fig. c, d between the results of measured deflections f on specimens of 1.6 mm thick welded conventionally using GTAW and those welded using LSND welding technique for stainless steel (Fig. 5, c) and aluminum alloy (Fig. 5, d). Completely buckle-free ($f = 0$) results were achieved when the optimized technological parameters for LSND welding techniques were selected.

As demonstrated above, designers and manufacturers who suffer from problems of buckling could now adopt a new idea that buckling is no longer inevitable with LSND welding technique. Buckling can be prevented completely and residual stresses can be reduced significantly or controlled to a level lower than σ_{cr} at which buckling occurs.

Successful results in preventing buckling distortions were achieved in manufacturing thin-walled jet engine cases of nickel base alloys, stainless steels as well as rocket fuel tanks of aluminum alloys where the acceptable allowance of residual buckling deflections f at a weld length of L should be limited to the ratio of $f/L < 0.001$ (Ref. 12).

Localized Thermal Tensioning — LSND Welding with a Trailing Spot Heat Sink. Over the past 10 years, progress has been made at BAMTRI in seeking active in-process control of welding buckling to exploit a localized thermal tensioning technique using a trailing spot heat sink. The heat sink moving synchronously with the welding arc creates an extremely high temperature gradient along the weld bead within a limited area of high temperature zone close to the weld pool (Fig. 2). In this innovative method, the preset heating (as shown in Fig. 1) is no longer necessary. The formation of specific inverse plastically stretched inherent strains ε_x^p in the near arc zone behind the welding pool is dynamically controlled by a localized trailing thermal tensioning effect induced between the welding heat source and the spot heat sink along the weld bead (Fig. 2).

With the specially designed device attached to the welding torch, an atomized cooling jet of the trailing spot heat sink impinges directly on the just solidified weld bead. Liquid coolant, such as CO_2, Ar, N_2 or water, could be selected for atomized cooling jet. Atomizing the liquid coolant is essential to improve the efficiency of intensive cooling rather than using liquid jet directly impinging the weld bead. To protect the arc from the possible interference of the cooling media, there is a co-axial tube to draw the vaporized media out of the zone nearby the arc. The technological parameters for the trailing spot heat sink and all the welding procedures are automatically synchronously-controlled with the GTAW process. The dominating factors: the distance between the heat source and the heat sink, the intensity of the cooling jet can be selected properly to reach a buckle-free result.

In systematic investigations, finite element analysis with a model of cooling jet impinging the weld bead surface is combined with a series of experimental studies (Refs. 13–17). Comparisons between the temperature fields on conventional GTA welded titanium plate and on plate welded using technique with the trailing spot heat sink are given in Fig. 6.

In this case, welding with trailing spot heat sink was carried out using the same parameters as in conventional GTA welding. The flow rate of cooling medium (atomized water) was selected at 2.5 ml/s. The distance between the arc and cooling jet were regulated from 80 mm to 25 mm. It can be seen clearly (Fig. 6, b, d) that in welding with spot heat sink there is a deep temperature valley formed by the cooling jet behind the weld pool. An extremely high temperature gradient from the peak to the valley is created. The 800 °C and 400 °C isotherms in front of the heat sink are severely distorted pushing forward closer to the weld pool (see Fig. 6, d).

The abnormal thermal cycles by welding with trailing spot heat sink produce correspondingly the abnormal thermo-elastic-plastic stress and strain cycles in comparison with the cycles formed by conventional GTAW.

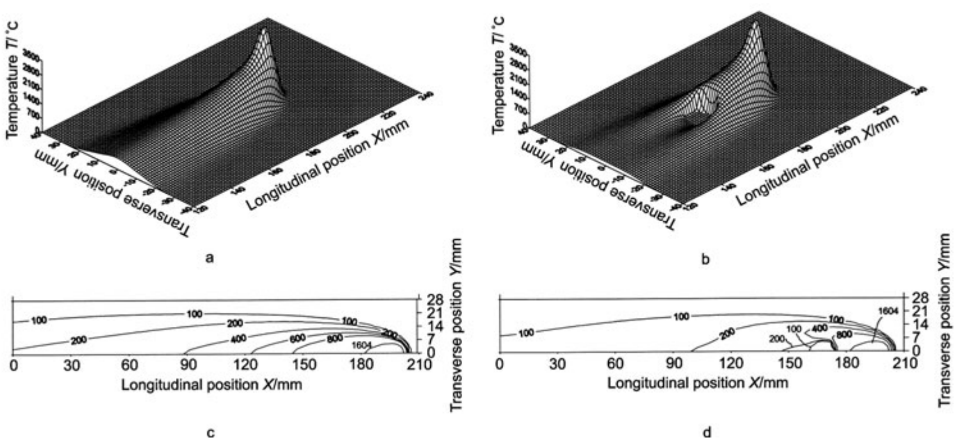

Fig. 6. Temperature fields and isotherms on Ti–6Al–4V (2.5 mm thick) plate (Ref. 16), welding parameters: 200 A, 12 V, 12 m/h; a, c — conventional GTA welding on copper backing bar; b, d — welding with trailing spot heat sink

Obviously, the localized thermal tensioning effect is acting only within a limited zone behind the weld pool.

The compressive plastic strains formed before in the just solidified weld zone can be compensated properly by the inherent tensile plastic strains in the area of temperature valley.

In welding with trailing spot heat sink, both the value of inherent plastic strains and the width of its distribution can be controlled quantitatively by selecting the proper technological parameters: the distance D between the welding heat source and the heat sink (see Fig. 7) as well as the intensity of the heat sink.

For a selected intensity of heat sink, the closer the heat sink to the heat source (the shorter the distance D), the stronger is the localized thermal tensioning effect. For example, at the distance $D = 25$, the residual plastic inherent strain $\varepsilon_{\mathrm{x}}^{\mathrm{p}}$ on the weld centerline even changes its sign from negative to positive, and the residual stress on the weld centerline changes from tensile to compressive correspondingly.

Fig. 8 gives some typical examples from the systematic investigation program. As shown in Fig. 8, a, the peak tensile stress in weld on mild steel plate welded using conventional GTAW reaches 300 MPa (curve 1) and the maximum compressive stress in the peripheral area is about 90 MPa which causes buckling with deflections more than 20 mm in the center of specimen of 500 mm long. In the case of welding with the trailing heat sink the patterns of residual stress distribution (curves 2,3,4) alter dramatically with different technological parameters, even with the compressive residual stresses in the centerline of the weld. The reason is that the shrinkage induced by the great temperature gradient between the arc and the cooling

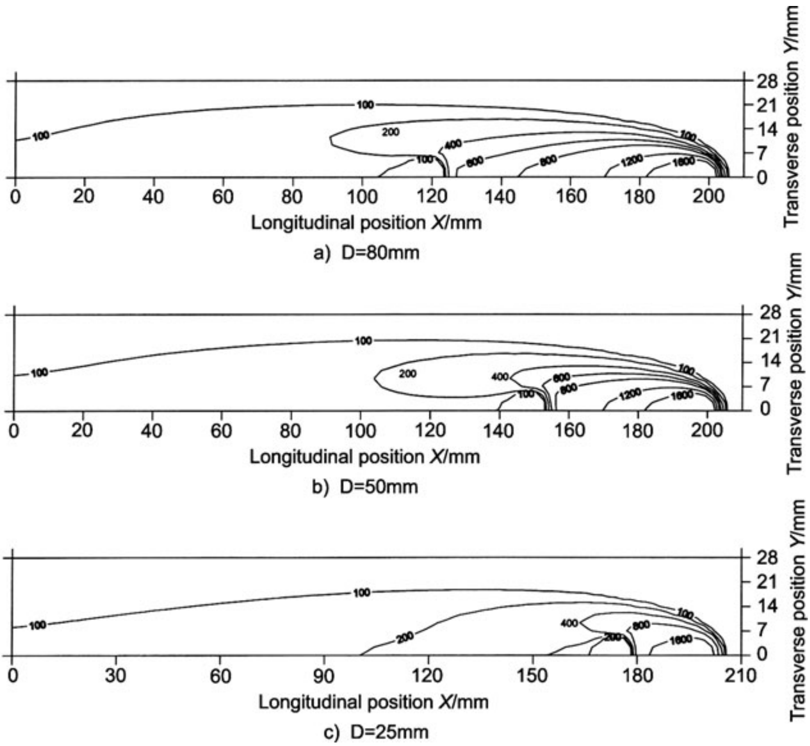

Fig. 7. Isotherms on titanium plate with different distance D between the arc center and the cooling jet center (Refs. 16, 17)

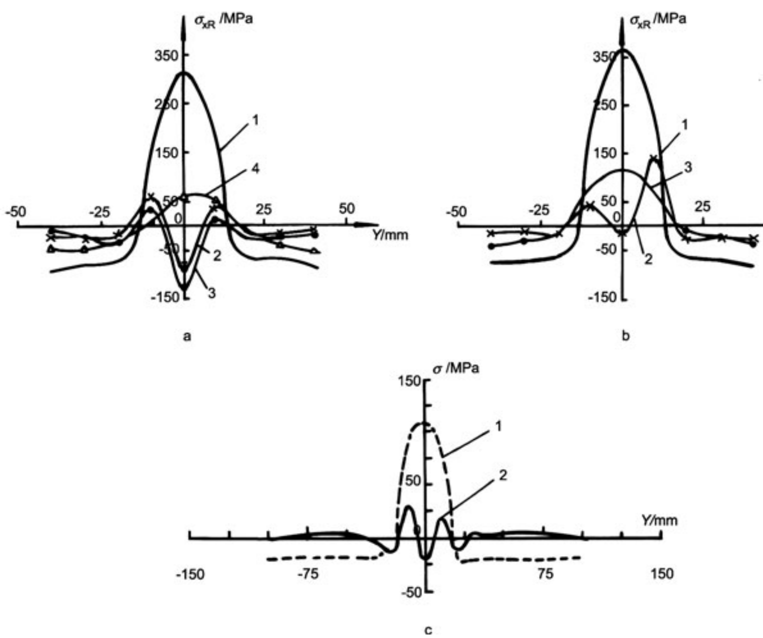

Fig.8. Measured residual stress distributions on plates 1 mm thick mild steel (a), stainless steel (b) and 2 mm thick aluminum alloy (c) welded using conventional GTAW (curve 1) and by use of welding with trailing spot heat sink (Refs 13–15)

jet tends not only to compensate the welding compressive plastic strains but also to alter the sign of residual strain to its opposite. Results show that the distance D has more significant influence on both ε_x^p and σ_x in controlling buckling on thin materials. After welding with the trailing spot heat sink, the specimens are completely buckle-free and as flat as original before welding. Similar results were obtained as shown in Fig. 8, b, c on stainless steel and aluminum plates.

Metallurgical and mechanical examinations show that the cooling jet medium gives no noticeable influence on the titanium weld joint properties. Actually the cooling jet is impinging directly on the solidified weld bead at a temperature less than 400 °C as shown by the distorted abnormal isotherm of 400 °C in front of the heat sink (Fig. 7, c).

Recent progress in numerical simulation of welding phenomena offers researchers powerful tools for studying in more detail of welding thermal and mechanical behaviors. These tools allow for the prediction of precise control of the abnormal temperature fields and therefore the abnormal thermal elastic-plastic cycles created by the possible variable combinations of the heat source–heat sink welding techniques. It is expected that a variety of coupled heat source-heat sink processes are feasible for not only welding distortion controlling but also defect-free welds. For example, the device for trailing spot heat sink can be attached not only to the GTAW torch but also could be coupled to other heat sources like laser beam or friction stir welding tool to control distortion, and to improve joint performances as well.

Conclusions. 1) Low Stress No Distortion (LSND) welding techniques for thin materials can be implemented using either the whole cross-section thermal tensioning effect or the localized thermal tensioning effect.

2) Basic principles and mechanism of LSND welding techniques are clarified through experimental studies and theoretical analyses with FEA.

3) For LSND welding using the whole cross-section thermal tensioning, the necessary condition is to create an adequate preset temperature profile coupled to the welding temperature field whereas its sufficient condition is to keep the thin plate elements in a plane position without any transient loss of stability during welding.

4) In executing DC-LSND welding technique using localized thermal tensioning, the dominating technological parameters are: the distance between the heat source and the heat sink and the intensity of the heat sink. For engineering solution and industrial application, optimized technological parameters are recommended based on FEA results.

5) Both LSND welding techniques have been applied successfully in sheet metal industries to satisfy the stringent geometrical integrity requirements especially to ensure dimensional consistent fabrication of aerospace components.

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