CRITICAL REVIEW

Forming-based geometric correction methods for thin-walled metallic components: a selective review

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Abstract
Geometric correction processes contribute to zero-defect manufacturing for improved product quality. Thin-walled metallic components are widely used in numerous applications such as electric vehicles and aircraft due to the lightweight feature, facilitating to achieve zero-emission goals. However, many components suffer geometric imperfections and inaccuracies such as undesired curvatures and twists, seriously affecting subsequent manufacturing operations, for example, automatic welding and assembly. Geometric correction techniques have been established to address these issues, but they have drawn little attention in the scientific community despite their wide applications and urgent demands in the industry. Due to the strict geometric tolerances demanded in high-volume automated production, it is urgent to increase the knowledge needed to develop new techniques to address future industrial challenges. This review paper presents an overview of typical geometric defects in thin-walled components and clarifies the associated underlying generation mechanisms. Attempts have also been made to discuss and categorize geometric correction techniques based on different forming mechanisms. The challenges in correcting complex thin-walled products are discussed. This review paper also provides researchers and engineers with directions to find and select appropriate geometric correction methods to achieve high geometric accuracy for thin-walled metallic components.

Keywords Geometric correction · Thin-walled components · Geometric defects · Metal forming

1 Introduction

Developing a circular economy is critical in reducing environmental impacts caused by human activities [1]. In modern industrialized economies, the metal-forming related industry is one of the main contributors to GDP; for example, it takes up about 7% of the US GDP and 28% of the German GDP [2]. An aluminium extrusion company reported that every year around 1.1% (1.9 over 17 million kg) of its products were rejected due to the quality problems in the manufacturing chain such as extrusion, forming and

heat treatment, and about 5% of the rejections were caused by geometry-related defects such as twists [3, 4]. This causes delivery delays, increased energy consumption and extra production costs. Geometric correction, also commonly called 'calibration' in industry, is a sustainable strategy to revive non-conformance products [5, 6]. Geometric correction aims to improve product quality by reducing geometric imperfections and inaccuracies through different secondary processing methods or integrated processes including turning, polishing and slight reforming and reshaping. Among these methods, forming-based geometric correction techniques are favoured due to their advantages of high accuracy, high efficiency, low cost and the possibility for inline process integration. Therefore, in this study, forming-based geometric correction techniques are highlighted and reviewed.

Thin-walled structures are widely used in different engineering sectors, such as automotive and aerospace industry, mainly because of their high strength-to-weight ratio. They are particularly used as a lightweight solution for reducing energy consumption and CO_2 emission in transportation sectors. For example, it was reported that a

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decrease of 10% in vehicle weight could generally improve fuel efficiency by 6–8% [7]. Some representative examples of the applications of thin-walled structures in different sections are shown in Fig. 1.

Geometric defects are frequently associated with manufacturing of thin-walled components, such as buckling, wrinkling, twisting and thickness inhomogeneity [13, 14]. However, tight geometric tolerance is of crucial importance for digital manufacturing for complex thin-walled components; for instance, automated welding and assembling processes in mass manufacturing normally require stringent control of the part tolerance to ensure the safe assembly and the quality of final components [15, 16]. Meanwhile, for improved structural integrity, functionality and aesthetics, the geometries of thin-walled structures are becoming complex, as shown in Fig. 1 [17–20]. This in turn puts forward new manufacturing challenges for such complex thin-walled products with tight geometric tolerance requirements.

Great efforts have been made to optimise and control manufacturing processes to achieve products with high geometric accuracy. For example, buckling and springback in aluminium sheet forming were considered in the design stages of manufacturing, which effectively avoided geometric inaccuracies by optimising the die design and controlling the process parameters [21–24]. Advanced algorithms including the Taguchi method, principal component analysis method, and non-dominated sorting genetic algorithm were developed to optimise the process parameters for high dimensional accuracy in micro-milling thin-walled microparts [25]. However, many unpredictable noise-like factors in manufacturing processes (e.g., machine vibration, unexpected temperature inhomogeneity, tool wearing and fluctuation of process parameters), as well as other factors before or after the main manufacturing processes (e.g., uncertain dimensional deviations, material property variation, unexpected external loadings and temperature variations in the storage or transport stages), do exist [20]. These factors can hardly be predicted and controlled, which could cause products failing to meet the tolerance requirements. As a consequence, the geometric issues will significantly affect productivity and cost in both mass and low-volume production [26]. Instead of rejecting unqualified products, it is desirable from multiple perspectives to minimize these geometric defects by geometric correction.

Corresponding correction techniques have been developed to assist in improving geometric accuracy through different forming mechanisms. Springback is critical for high geometric accuracy, which is inevitable and hard to predict due to its sensitivity to factors such as residual stress [27]. Overbending and stretch bending have been used to correct springback-deduced geometric defects [28, 29]. Regarding some hard-to-deform materials, thermal/hydraulic corrections are applied because of the high formability and capability of reducing springback [30, 31]. For a short cyclic time, impulse corrections, such as electrohydraulic or electromagnetic techniques, have been introduced for high geometric precision [32, 33]. The residual stress-caused distortion can be corrected by heat treatment. For example, a hot sizing process, including heat treatment with die constrains, was used to correct distortions caused by welding [31]. The development of flexible or multipoint forming techniques provides new opportunities for geometric correction, enabling corrections to be conducted during the forming processes by introducing simple tools [34–39]. However, there is a lack of systematic study that compares and analyses geometric correction methods for specific geometric defects. Meanwhile, the industry has limited scientific guidance tools to select the right techniques or develop new processes for
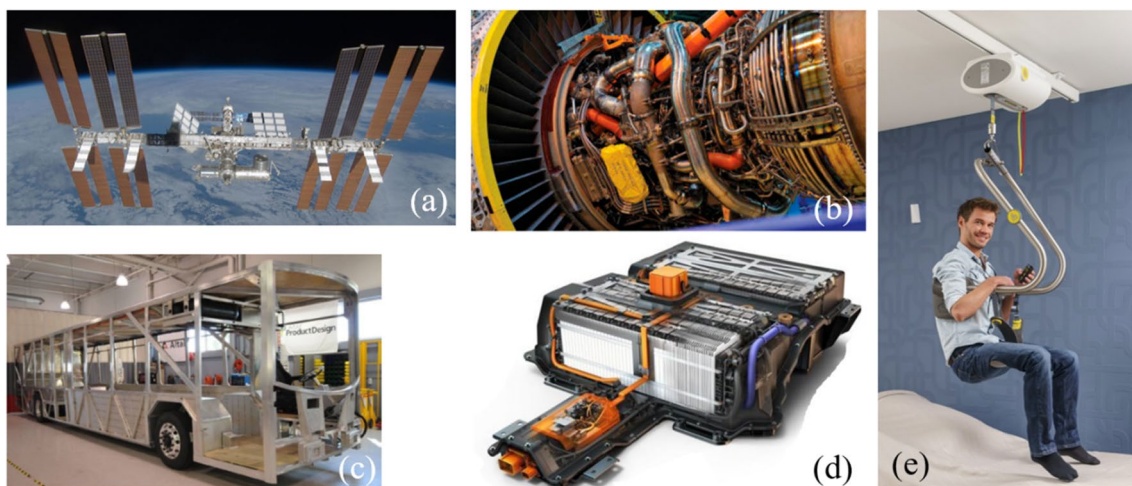
Fig. 1 Wide applications of thin-walled metallic components: **a** the International Space Station [8], **b** the aero engine [9], **c** the mass transit bus [10], **d** electric vehicle battery package [11] and **e** lifting and body support system [12]

specific needs. Therefore, it is important to summarise the techniques available and to offer some scientific guidance for the industries as well as highlight recommendations for further research direction in this field.

To advance the understanding of geometric correction techniques and provide scientific guidance to developing new correction techniques, this study seeks to answer the following research questions:

(1) What are the typical geometric defects associated with thin-walled components, their causes and geometric control strategies?
(2) What are the existing geometric correction methods?
(3) What are the current gaps between existing methods and industrial demands and the suggestions to fill the gaps?

The remaining of the paper is organized as follows: Section 2 summarizes the main geometric defects, along with their fundamental causes and control strategies. Sections 3 and 4 overview the geometric correction techniques in the literature. The structure is presented in Fig. 2, as guidance for the audience to follow this paper. Section 5 discusses and compares all the mentioned techniques, highlights the scientific gaps and provides suggestions for future development.

2 Geometric defects and control strategies

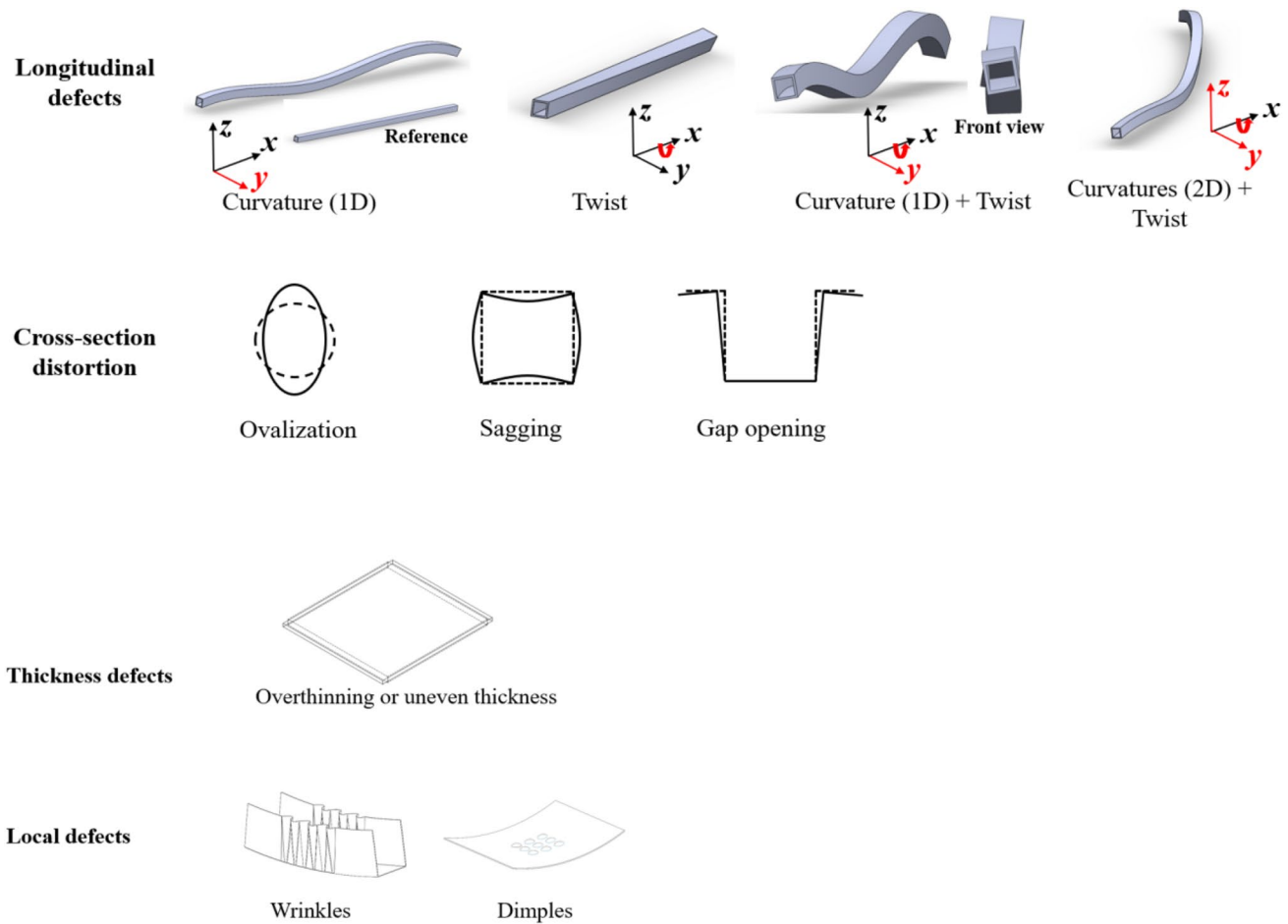### 2.1 Clarification of geometric defects and causes

Thin-walled structures refer to structures with one dimension significantly smaller than the other two, particularly including the parts made by sheets, profiles, tubes, etc. [40]. Depending on the specific applications, various metallic materials, such as steel, aluminium, titanium, copper,

magnesium and their alloys, are commonly used for manufacturing such products. Some typical geometric defects are summarised in Fig. 3. Based on the specific geometric characteristics, these defects are categorized as longitudinal defects, cross-sectional distortion, thickness defects and local defects. As there is no common definition of geometric defects in the scientific community and industry, there may be some differences between different industrial definitions.

- Undesired curvature and twisting typically occur on long products along the longitude direction, defined as longitudinal defects here. Four types of longitudinal defects are categorized based on the directions of the curvatures and with/without twisting, as shown in Fig. 3. They can be caused by mechanisms taking place at different stages along the manufacturing chains. For example, residual stress caused by plastic deformation or thermal processes can cause curvatures and twisting [41, 42].
- Regarding cross-sectional distortions (referring to defects occurring on the cross sections), ovalization is commonly found in tubes due to varying transverse stress components around the perimeter of the cross section upon bending [42, 43]. Sagging is a result of the same mechanisms in non-round hollow profiles [44, 45]. For open U shapes, for example, undesired gap openings can be easily found in straight, non-bent extruded profiles, caused by mechanisms such as uneven temperature distribution during cooling or unbalanced material flow [15].
- Along the thickness direction, excessive thinning and uneven thickness often happen to the thin-walled members under large stretching. This may occur as a result of anisotropy or variations in constraints, for example, uneven friction conditions [46–48].
- Local defects refer to defects occurring locally such as wrinkles and dimples. Wrinkles are caused by the high in-plane compressive stress, resulting in local instabili-

Fig. 2 Overview of forming-based geometric correction techniques
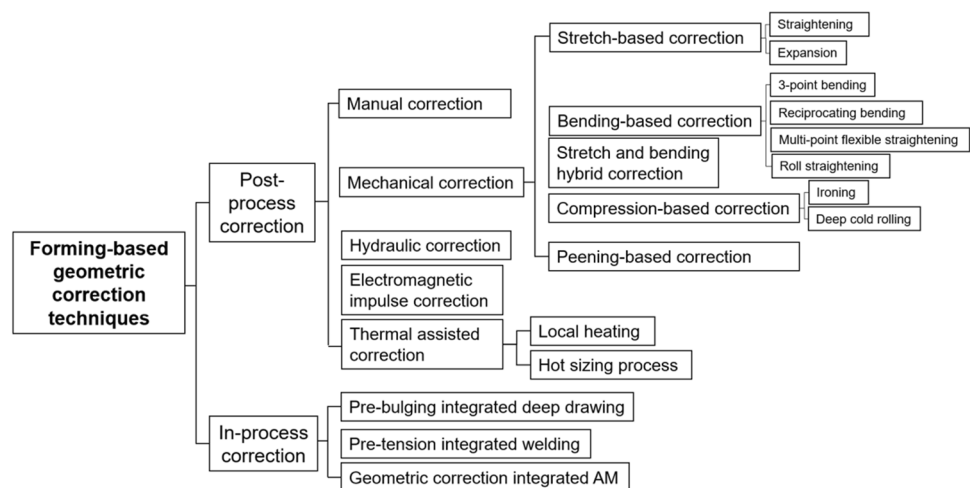
Fig. 3 Schematic illustration of geometric defects in thin-walled metallic components, including longitudinal defects, cross-sectional distortion, thickness defects and local defects (the solid lines show the defects, with the dashed lines representing the designed structures)

ties that create multiple buckling formations [49, 50]. Dimples are commonly found in the area under strong stress concentrations caused by tools such as during the incremental sheet forming [51, 52].

2.2 Geometric control strategies

Different solutions have been used to improve products' geometric accuracies. Based on if corrections are included, these solutions can be summarised into two groups, as compared in Fig. 4.

Figure 4a illustrates the geometric control strategies without correction. During the design stage of the main manufacturing process such as forming, welding or AM, the geometry- and process-related parameters are usually decided based on theoretical analysis and experience. If the final dimension of the product (D_f) falls within the tolerance Δ, the products are accepted as qualified. Otherwise, the products will be rejected. The number of rejected products can be reduced by iteratively modifying

and adjusting tooling or process-related parameters. However, in some cases, the noise-like parameters cannot be effectively controlled. Therefore, the correction processes are necessary to be included to minimise the number of unqualified products.

The geometric control strategy including correction is shown in Fig. 4b. The correction process has two purposes: (i) to revive the rejected products by narrowing the dimensional deviation to the required tolerance Δ and (ii) to meet the increased demand for a tighter dimensional tolerance (when $\Delta_n < \Delta$) required for digitalised production or improved performance in service. The geometric correction can be conducted in a separate operation after the main manufacturing process (called post-process) or within the main manufacturing process (called post-process correction). Note that not all the parts are correctable with the existing techniques, for example, parts with severe wrinkles [53]. Thus, only certain parts, for example, with a dimensional deviation within Δ_n and Δ_c, will be selected for correction.

(a) Without correction
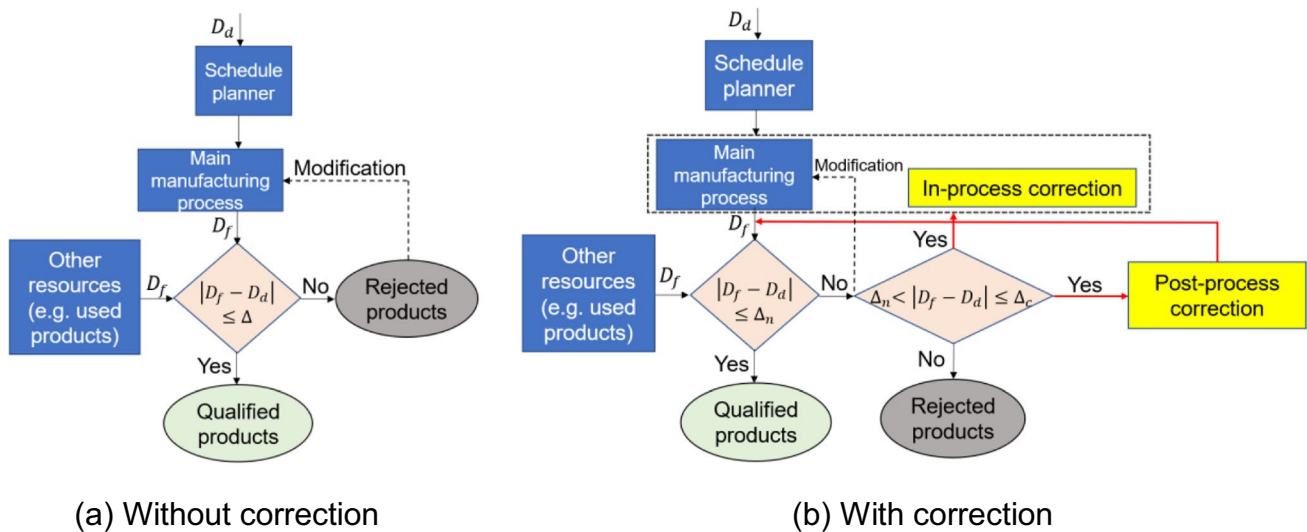
(b) With correction

Fig. 4 Dimension control strategies in manufacturing chains **a** without correction when the product dimension tolerance is Δ and **b** with correction for a tighter dimensional tolerance Δ_n (D_d means the designed dimension; D_f represents the final dimension; Δ represents required dimensional tolerance; Δ_c represents critical dimensional tolerance for rejected products)

3 Post-process correction

This section reviews existing post-process correction based on their principles including manual, mechanical, hydraulic, electromagnetic and thermal correction methods. The advantages, limitations and development of these techniques are discussed.

3.1 Manual correction

Manual correction is used to correct the geometric defects by repeatedly hammering the workpiece with the assistance of tools such as platforms, clamps, anvils and hammers [54]. Figure 5 shows a schematic view of a typical manual correction method, whereby the curvature of an L-shaped profile is manually tuned [55]. The desired curvature can be achieved when the profile matches the bottom block using repeated hammering. Due to its flexibility, this method is capable of correcting various geometric defects such as local bulging and twisting [54].

The quality outcome of this technique highly depends on the operator's experiences. In addition, manual correction is very time- and cost-consuming. For example, the cost for the geometric correction was estimated to be 50% of the total manufacturing cost for one part in one case [56].

Automation has been developed to realise high-precision control of product quality [57]. For example, a camera was used to capture the geometric defects occurring during metal hammering, based on which the hammering strategy was updated accordingly [58, 59]. In robotic blacksmithing, the robots are used to imitate the behaviours of the technicians to complete the whole manufacturing process [60].
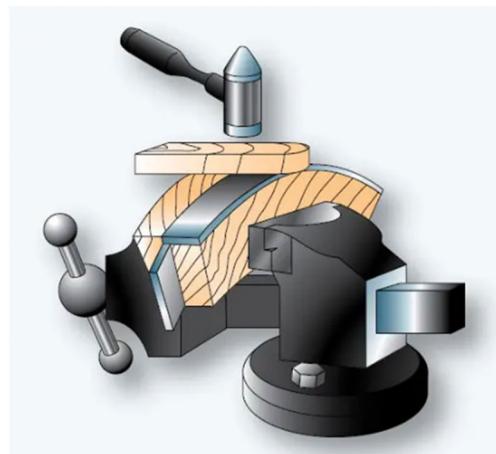

Fig. 5 Schematic view of manual correction of geometric defects [55]

Therefore, it is very promising to learn from traditions and develop advanced correction techniques for high-precision products [57].

3.2 Mechanical correction

Mechanical correction methods improve the geometric accuracy of components by applying mechanical loading using different machines in combination with specially designed tools. Based on their loading modes, various mechanical correction techniques have been developed, including stretching, bending, compression and peening-based methods, as shown in Fig. 6. Different kinds of geometric problems such as undesired curvatures, large gap opening and
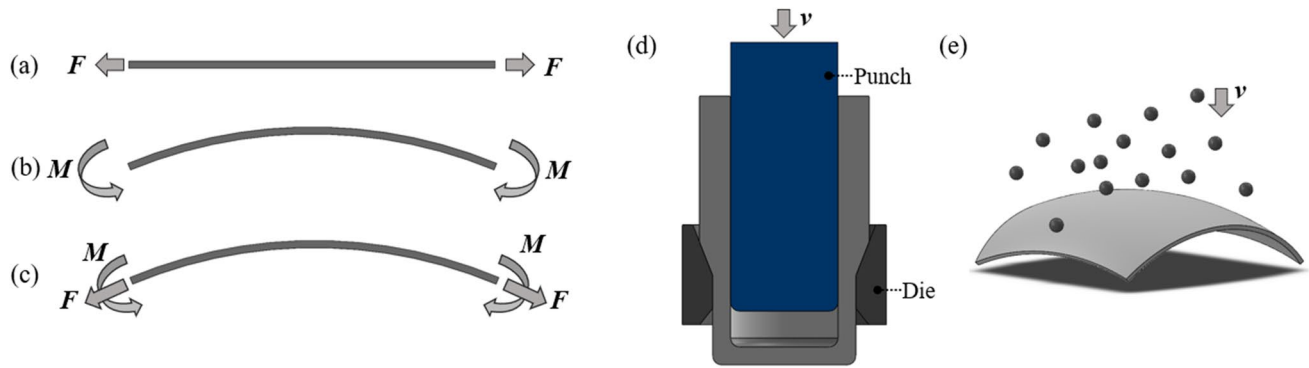
Fig. 6 Schematic illustration of typical mechanical correction mechanisms: **a** stretching, **b** pure bending, **c** stretch bending, **d** ironing and **e** shoot peening (*F*: force; *M*: moment; *v*: velocity)

wrinkles, can be corrected within the geometric tolerance of the product [61].

3.2.1 Stretching-based correction

The stretching-based correction has been used to improve the straightness of long parts such as extruded profiles or the flatness of a sheet by applying tension to create minor plastic strains on the parts [61, 62]. Depending on the geometry of the part, the stretching can be applied in the axial direction or the hoop direction for hollow circular parts. Uniaxial stretching is widely used to correct the straightness of semi-finished long products, reducing undesired curvatures in multiple planes. For the ultra-long profiles, additional curvatures may occur during the straightening process. Thus, segmental stretching is applied (in Fig. 7), which can mitigate the occurrence of new defects and improve geometric accuracy [63].

In addition, stretching can be applied in the hoop direction, also called expansion, which is able to improve the circularity of thin-walled pipes. An example is shown in Fig. 8a, in which the equipment is designed to correct thermally induced tube distortion caused by welding [64]. Stretching deformation along the hoop direction is generated by moving the expandable tools in the radial direction. As shown in Fig. 8b, the lengthwise inflection at the centre of a 12-m-length steel tube is reduced by nearly 50% [64].

3.2.2 Bending-based corrections

Bending-based correction methods can be used to improve the straightness of long parts and the curvature of bent parts.

Three-point bending-based straightening is commonly used to improve the straightness of long parts [65]. Usually, two ends of the profile are supported on the two fulcrums, and vertical loading is applied in the middle of the profile
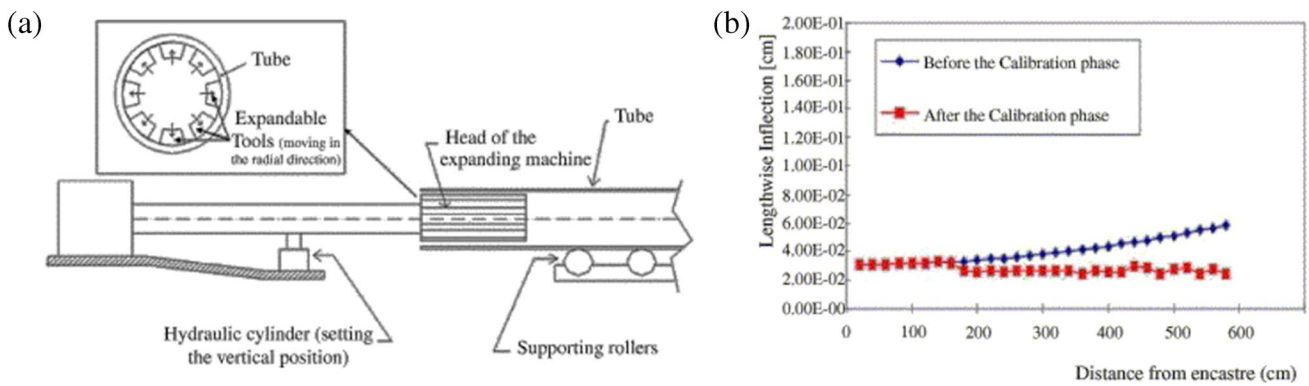

Fig. 7 Straightening process for correcting curvatures on long profiles [63]

(a)

(b)

Fig. 8 Schematic illustration of **a** the tube expanding machine and **b** the calibration results [64]

(ready-to-correct region). Given the springback after unloading, a higher loading would be applied to compensate for the springback and achieve the desired dimension.

Reciprocating bending is applied when the perfect straightening cannot be achieved in a single bending step. This particularly applies to long profiles with large deflection and multiple peaks [66, 67]. The principle is shown in Fig. 9. Reciprocating bending can also mitigate the initial residual stress [26]. The profile is under multiple bending and unloading with the rotation of the profile after each bending [68]. In a four-point reciprocating bending case, the straightness (defined as the residual deflection over the total length) of 0.1% was achieved for both the C-shaped and S-shaped initial curvatures [66].

Multi-point flexible straightening was developed to straighten long profiles with variable initial curvatures, including curvature unification and overbending straightening [69]. A typical multi-point straightening process is shown in Fig. 10. The curvature unification aims to correct the different curvature portions to a unified curvature by controlling the positions of the multiple dies. The overbending process is designed to achieve the designed straightening with compensation of elastic springback. With the

considerations of deformation mechanisms, the straightness of 0.2% on a 320-mm aluminium H-section profile is achieved [69].

The roll straightening process was developed for high efficiency due to its continuous forming feature. Based on the complexity of geometry, there exists the simple two-roller continuous straightening process and the more complex multiple-roller straightening process, as shown in Fig. 11 [70, 71]. In two-roll straightening (in Fig. 11a), a bar/tube to be straightened is bent and simultaneously rotated as it passes between a set of two rolls, in which one is convex and the other is concave [72]. Multiple rollers are often used in roll straightening for continuous correction where high efficiency is demanded, as shown in Fig. 11b. A set of smaller rollers are positioned above the profiles, and the set of larger ones is under the profile, leaving the profile in a state of continuous bending. For thin-walled tubes, however, buckling occurs easily between two adjacent rollers, if the deformation is too large. More rollers are required to avoid buckling, which demands more cost and is less favoured by the industry. Thus, the two-roll straightening is more popular for straightening thin-walled tubes [73]. Furthermore, two-roll straightening shows high

Fig. 9 Schematic diagram of reciprocating bending Bauschinger-like effect of AZ31 magnesium alloy wide sheet during the straightening process [68]
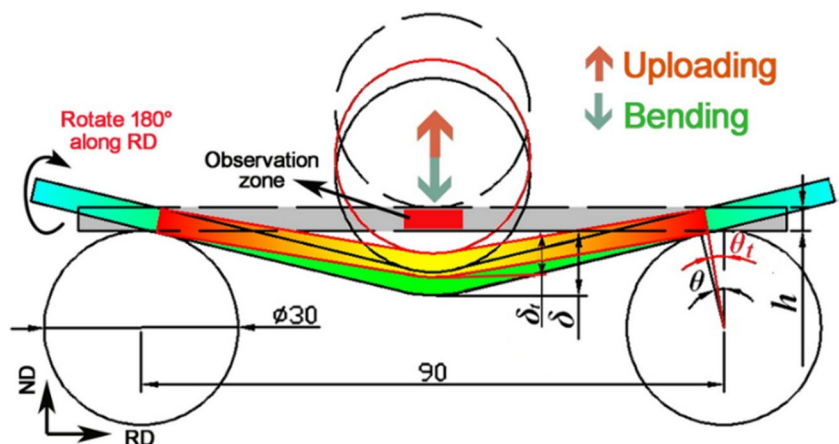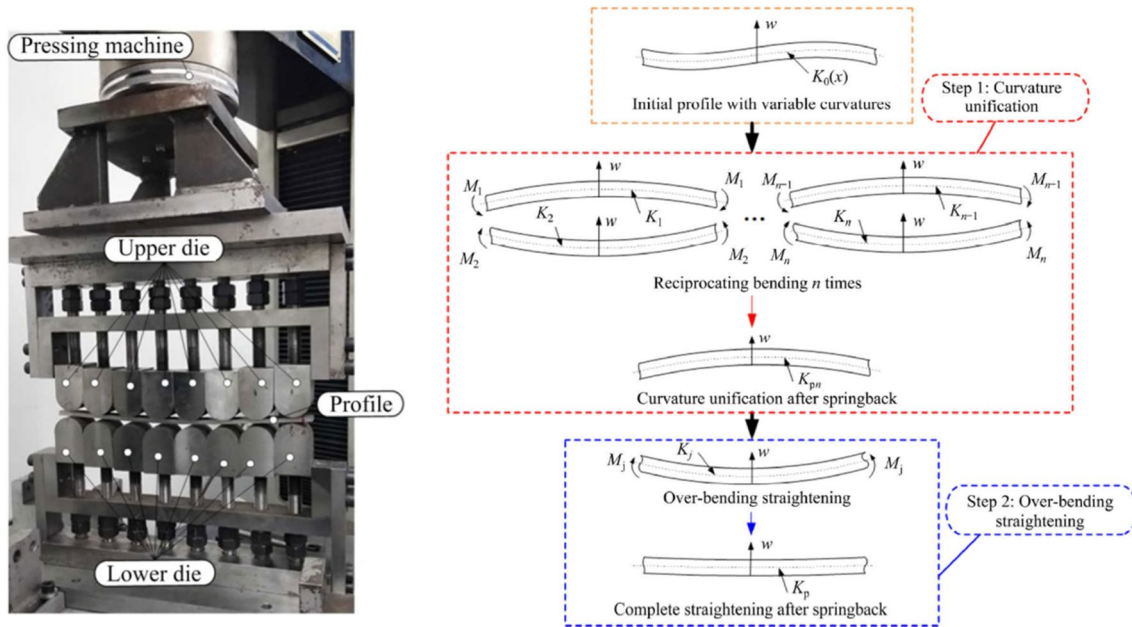
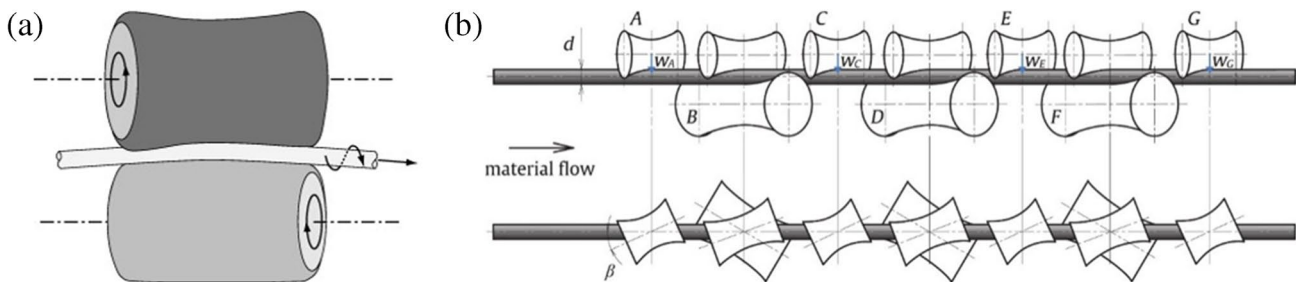**Fig. 10** Multipoint flexible straightening machine and loading process [69]

Fig. 11 Schematic view of **a** two-roller and **b** multiple-roller straightening process [70, 71]

straightness precision in practice compared with the multiple rollers [74]. To balance the production efficiency and straightness precision, a three-roll continuous straightening process was developed, enabling a straightness of less than 0.2% and an ovality within 0.5% [73, 75].

The setting-round process is used to correct the ovality and cross-sectional distortion in the thin-walled pipes with large diameters and long lengths. The principle is shown in Fig. 12a. The pipe is driven continuously along the hoop direction by the inner roller and two outer small rollers [76–78]. The segment of the tube supported by the external roller is mainly under bending [77]. Experimental research shows that the residual ovality of a longitudinally submerged arc welding pipe can be reduced to less than 0.7% without cross-sectional distortion, which demonstrates the good capability of this process [76]. The residual ovality under the different initial ovalities is shown in Fig. 12b.

3.2.3 Hybrid stretch and bending correction

Figure 19 illustrates a mechanical correction process for a U channel. The initial geometry differs from the nominal geometry in terms of the opening gap (in Fig. 13a). During the calibration process, the wedge moves downward, pushing the blocks downward and sideward, and the profile fully contacts with the bottom die. Local bending of the sidewalls and stretching of the bottom flange take place (in Fig. 13b). By tailoring the deformation process of the bottom and sidewall, the springback on the top gap opening can be eliminated and the desired result can be achieved (in Fig. 13c). The hybrid stretching and bending technique was experimentally validated, showing that the process is capable of improving the maximum gap opening variations by 90%, which makes it promising for industrial application [15, 79].

Another technique with a similar mechanism was applied to correct the geometry of an automotive crush can with a

double chamber section, as presented in Fig. 14 [80]. The initial profile was in need of tight dimensional tolerances due to the metal inert gas (MIG) welding of a footplate to one of the ends. To achieve better tolerances, the lower and upper dies are applied with two mandrels inserted into two blocks. During calibration, the upper die moves downward
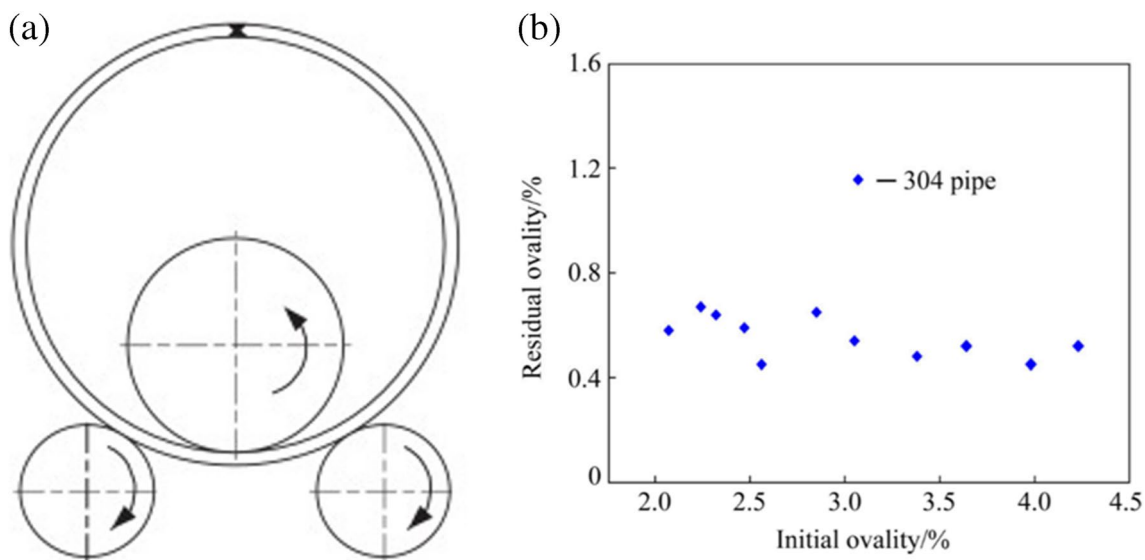

(a)   (b)

Fig. 12 **a** Schematic view of the setting round process [78] and **b** effects of initial ovality on residual ovality [77]
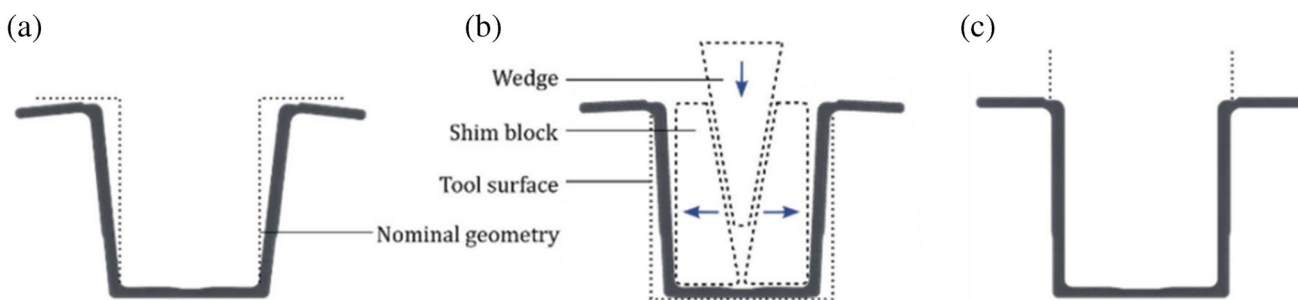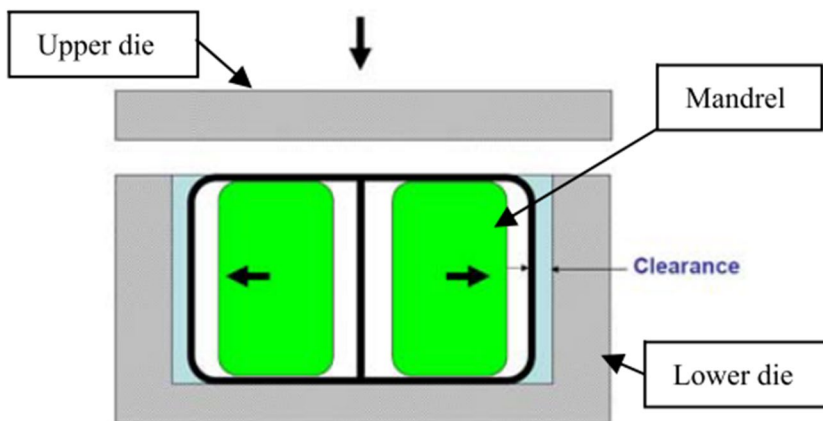

(a)   (b)   (c)

Fig. 13 Overview of the mechanical calibration process: **a** as-extruded geometry variation, **b** mechanical calibration strategy, and **c** calibrated geometry [15]

Fig. 14 Crush box calibration by stretch and local bending technique [80]

to flatten the upper and bottom surfaces with the interaction of the bottom die. Driven by the movement of the upper die, a mechanism ensures that the two mandrels move sideways, stretching the upper and lower flanges such that the external side walls (webs) get aligned with the tool surfaces. The experimental results show that this technique improved the dimensional accuracy of the exterior surfaces of the crush can by a factor of 5–10 [80].

The advantages of this technique include high dimensional capabilities. The disadvantages include low flexibility and high cost of the tools and machinery [37].

3.2.4 Compression-based correction

Ironing is the process of drawing a previously deep-drawn cup through an ironing ring with a moving ram, which can be used to improve surface quality by removing surface waviness [81]. One schematic illustration can be found in Fig. 6d. The compression along the radial direction can even out wall thickness deviations and remove the surface waviness [81, 82]. Cold rolling is commonly used in the tube manufacturing process after the pickling process for high geometric accuracy, surface quality and strength properties [83, 84]. The process is schematically illustrated in Fig. 15. The outside diameter of the tube is reduced under the action of rollers, leading to compressive plastic strain along the radial direction and homogeneous wall thickness [85]. The method also shows high efficiency in correcting the rectangular tubes [86].

Deep cold rolling has been used as a post-process treatment for additive-manufactured or welded products. It hardens the material surface and subsurface by regulated pressure and friction, enabling control of residual stresses
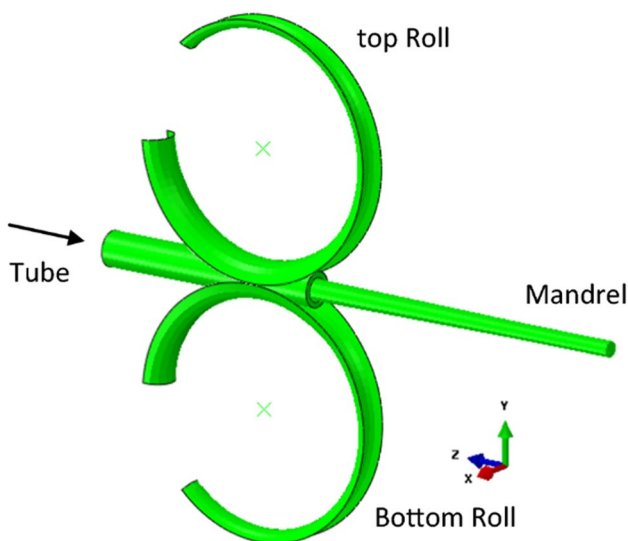
and preventing potential geometric distortion [87–89]. The principle is shown in Fig. 16. A roller moves along the surface of the products, providing a downward displacement. It has successfully been used in the aerospace industry for different materials, such as titanium (Ti-6Al-4V) [88, 90, 91] and nickel alloys (RR1000 and IN100) [89, 92].

Ultrasonic deep cold rolling incorporates the ultrasonic technique with the conventional deep cold rolling technique. It replaces the conventional static rolling force with the dynamic counterpart, ensuring fast and efficient control of the rolling pressure, which provides significant work hardening on the surface and high geometric accuracy [90, 93]. This method can create compressive residual stresses of around 900 MPa at 0.2-mm depth from the Ti-6Al-4V, which can greatly mitigate the occurrence of distortion.

Ironing and cold rolling show high capability for homogenizing wall thickness and smoothing the surface. The generated plastic deformation will also refine the surface grains and lead to improved mechanical properties.

3.2.5 Peening-based correction

Peening introduces plastic deformation under the action of compressive stresses locally in the workpiece by incremental hammering, as illustrated in Fig. 6e [94]. In the process, the shot acts like a hammer using hard particles, usually made from cast iron, steel or glass, against the surface of the workpiece. It causes compressive stresses on one side of the metal sheet, but tensile stress on the other side, leading to local deformation. With more shots, large plastic deformation can be achieved to correct the geometric defects. For example, carburized ring gears at a diameter of 122 cm, which were out of round as much as 3.17 mm, have been corrected to within 0.076 mm by shot peening [95].
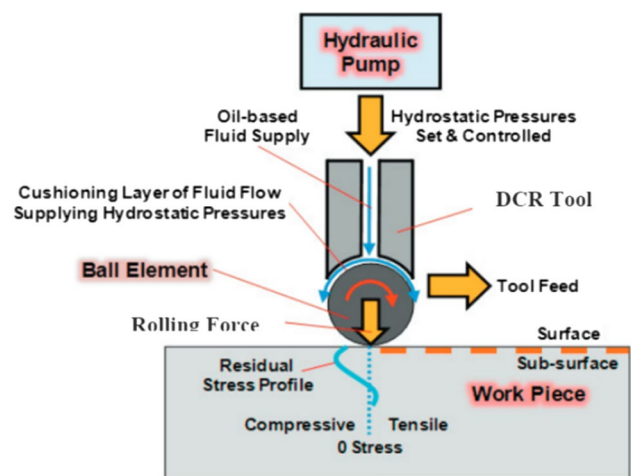

Fig. 15 Tube cold rolling process [83]

Fig. 16 Working principles of the deep cold rolling process [88]

The ultrasonic shot peening technique is commonly used to improve the geometric accuracy of welded parts. For instance, the thermal distortion of a welded aluminium sheet can be effectively calibrated at a correction rate of 90.8% by using this method [96]. More recently, 3D laser shock peening (3D LSP) was used, in which a periodic laser shock peening (LSP) treatment is added to a standard selective laser melting (SLM) process, as shown in Fig. 17. The distortion angle in this case is reduced by 75% [97]. To improve the accuracy, a control system circuit was designed to provide a high capability for controlling the peening force and frequency accurately [98].

This technique is highly flexible and can be used for various applications with a single machine. It is very promising to apply this technique to complex geometries by local deformation. However, it is mainly applicable for low-volume manufacturing due to the low efficiency of repeated shotting.

3.3 Hydraulic correction

Hydraulic correction is based on hydro-forming technology for sheets and tubes. By applying hydraulic pressure along with designed die cavities, the geometric defects (such as wrinkles or buckling) can be reduced or even completely removed. The correction process can be a stand-alone post-process or integrated with the main hydroforming process.

Buckling and wrinkling could occur during tube hydroforming due to improper inner pressure, as shown in Fig. 18a [53, 99]. However, the wrinkling was removed by secondary hydroforming with the same hydraulic tools at a higher hydraulic pressure (in Fig. 18b). In another case, the wrinkles on the rectangular steel tubes were flattened with rectangular tools and at a higher internal pressure [100]. However, not all wrinkles can be corrected to the desired geometries using this method. The wall thickness was found to be critical for correctability, and relevant theoretical analysis and experiments were taken to determine the critical thickness [50, 100].

For much higher precision, electrohydraulic forming was implemented after the preliminary forming process [101, 102]. Parts formed by sheet hydroforming and the hydraulic and electrohydraulic hybrid process were compared, as shown in Fig. 19. The hybrid process results in much sharper and more precise corners due to the instant pressure caused by the electricity discharge in the fluid [102]. The round corner generated in the deep drawing process was effectively removed by the subsequent electrohydraulic process. In addition to electrohydraulic forming, other flexible processes such as heat-assisted hydraulic forming and gas forming
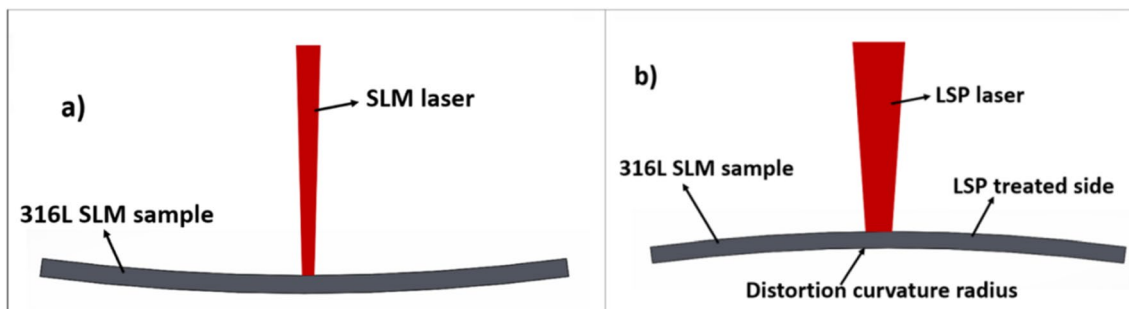
Fig. 17 **a** Exaggerated representation of an SLM sample with a concave distortion arc. **b** LSP-treated side of SLM samples with a convex distortion arc of $r = 1120$ mm [97]
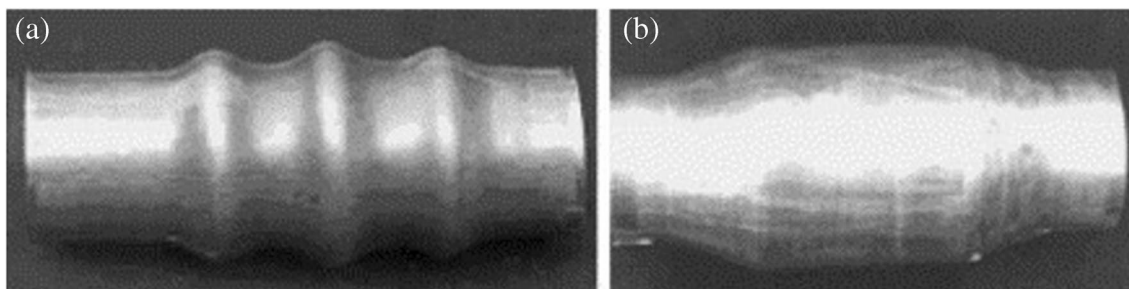
Fig. 18 Geometric correction in the tube hydro forming **a** wrinkling defects before correction and **b** corrected sample after the secondary forming with higher inner pressure [53, 99]
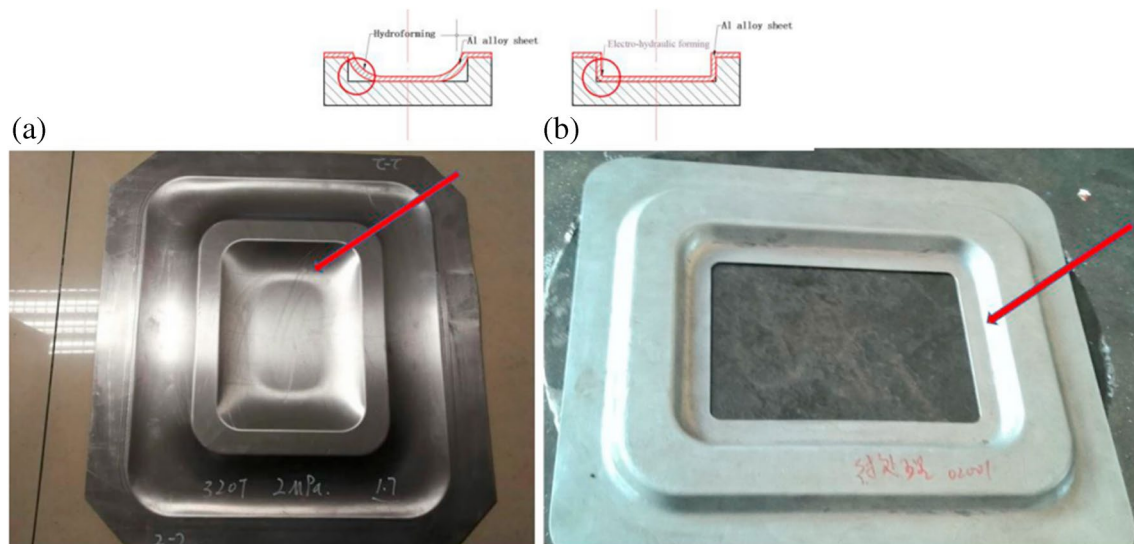
Fig. 19 Parts formed by **a** hydraulic forming and **b** hydraulic and electrohydraulic hybrid forming [102]

were suggested to correct geometric defects [103]. The springback generated in stamped high-strength steel parts was calibrated by pulsed electrohydraulic forming [104].

Hydraulic correction is advantageous for the geometric correction of wrinkling on the tubes, which cannot easily be achieved by mechanical correction. It does not require full contact with rigid dies, so less interactions happen between the die and workpiece, contributing to improve the material flow during forming and ensure a good finish surface. Although it can only be applied to correct a limited number of defect types with a relatively long cycle time and expensive machine tools, it shows some advantages that cannot be easily achieved by other correction methods such as surface removing waviness.

3.4 Electromagnetic impulse correction

Electromagnetic forming (EMF) correction is an impulse-forming technology, which uses Lorentz forces to reshape metals [32, 105, 106]. An example of an EMF sheet metal forming process is shown in Fig. 20. Lorentz forces are generated around the electric tool coil pushing the workpiece to the final geometry.

Iriondo et al. [107, 108] used the EMF technique to correct the springback-induced over-bent angle generated in the deep drawing process on a U channel. An industrially produced full-sized copper alloy rocket nozzle has been corrected by using EMF and, a considerable improvement in geometric accuracy has been achieved; meanwhile, four potential associated springback mechanisms were discussed.
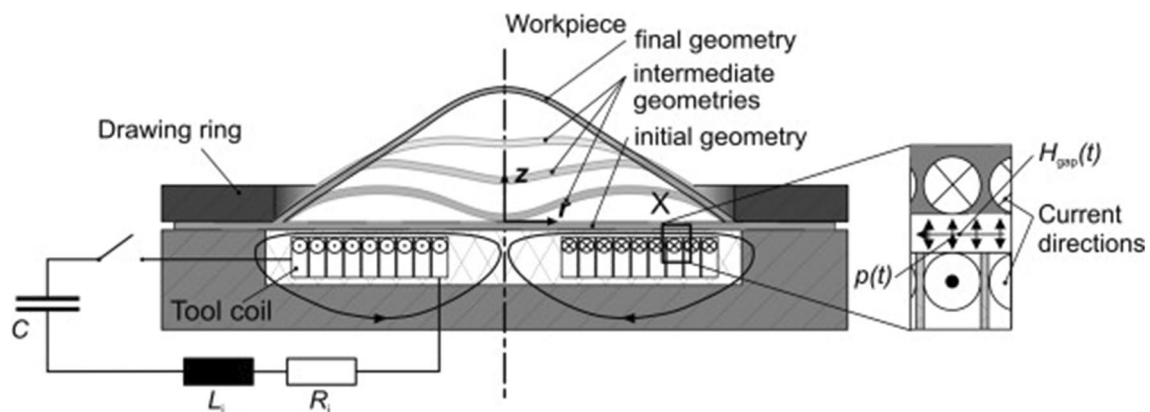
Fig. 20 One electromagnetic sheet metal forming process [106]

However, it is difficult to clarify the most significant mechanism contributing to the springback elimination due to the complex multi-physics nature [109].

EMF possesses a high potential for correcting geometric defects and achieving high precision. By adapting the coil shapes to the product configuration, the method provides flexibility to manufacture various-shaped products. However, the involved springback mechanisms are complex, including inhomogeneous pressure distribution, magnetic-plastic effects, and high-velocity effects. From a practical point of view, it is capable of expansion or compression of hollow tube-type parts and sheet metals. However, it is difficult to predict material deformation based on physics-based models, implying the need for the time and cost-consuming trial-and-error method. Therefore, to move its technology readiness to a higher level, multiple challenges prevail regarding both underlying mechanisms and process control, which need to be addressed before the wide industrial application of this technology.

3.5 Thermal-assisted correction

For some hard-to-deform metals, thermal correction is applied to avoid material fracture. This method not only increases material formability, but it can reduce springback providing a good basis for the high geometric accuracy [110]. Here, the two typical heating-assisted corrections are introduced as follows.

3.5.1 Local heating

Local heating specifically deforms the distorted region by local heats [30]. For example, on a flat metal sheet, the convex side at the distorted region can be heated up and then cooled down [30]. After cooling, the material on the heated side is shrunk, while on the other side, the material is stretched, which can induce plastic deformation and reduce or remove the undesired curvature. This process is also called flame correction in some references [111, 112].

However, severe temperature gradients are introduced in local heating, which could lead to high residual stress and unpredicted deformation. In practice, multiple trials are required before the desired results are achieved. Laser heating can better control the heating process by manipulating parameters such as laser power, laser spot diameter, scanning velocity and scanning path to reduce undesired distortion [113, 114]. Due to its simplicity and flexibility, local heating has been widely used to correct large-welded metal sheets.

3.5.2 Hot sizing process

The hot sizing process (HSP), a type of creep age forming, is mainly used in low-volume production [31]. In HSP, the distorted part is clamped in a contour-restraining fixture and heated to a target temperature when stress relief is expected to happen, and then kept at the temperature for several hours, allowing creep to transform elastic strain into permanent creep strain [115]. A typical schematic view is shown in Fig. 21a. The distortions of laser cladding and thin-walled titanium alloy components could be almost eliminated by heating the part to 730 °C and keeping this temperature for 300 min. Some results show that the HSP can reduce the maximum (out-of-spec) deflection from 2.94 to 0.45 mm (in Fig. 21b) [31].

In summary, thermal-assisted corrections have some advantages over room-temperature correction due to the higher formability and capability of reducing residual stress. Local heating provides simplicities and needs low cost, but it cannot guarantee production efficiency and high geometric accuracy. HSP is only applicable for creep-sensitive metals. Moreover, the process has limited applicability for high-volume production since each part under correction requires occupying a fixture for several hours to complete the process. Meanwhile, the heating equipment investment and energy requirement increases the manufacturing cost for large-sized components, especially for
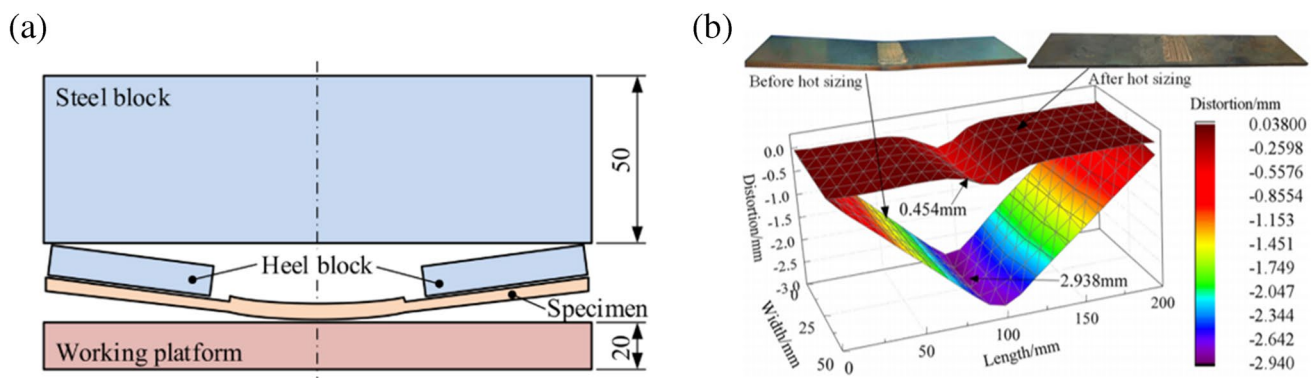
Fig. 21 **a** Diagram of the part clamping method for hot size process. **b** comparison of specimens before and after calibration [31]

volume production. Thus, thermal calibration is not very common in the industry and is not ready for mass manufacturing yet.

4 In-process correction methods

In addition to the post-process correction methods, some in-process correction techniques have been developed to manufacture the parts with desired tolerance within one operation. Here, the term 'in-process' refers to methods in which the correction is integrated into other operations used to add value to the product (other than the correction process itself), for example, integrating forming and calibration in one operation.

4.1 Pre-bulging-integrated deep drawing

Pre-bulging is used before a hydro-mechanical deep drawing process to avoid potential defects, such as wrinkling and over-thinning [116], as shown in Fig. 22. The blank is initially clamped between a binder and the die under a punch, and then pre-bulged around the punch-blinder gap due to the high pressure in the die cavity. The generated tangential stretch stress can partly offset the tangential compressive stress formed in the main deep drawing process, which can effectively avoid potential wrinkles as well as homogenise the wall thickness [116, 117]. The pre-bulging pressure is critical to the final thickness distribution and surface quality [118]. Too low or high pre-bulging pressure can lead to the material necking at the punch corner and even to the blank wall [119]. This method shows advantages in avoiding wrinkling and increasing the formability of deep drawn products by introducing an extra

process prior to the main forming process without introducing new tools or machines.

4.2 Pre-tension-integrated welding

The residual stress and related distortion are critical for the quality of welded parts. The application of pretension can counteract compressive stresses caused by uneven expansions in specific areas during the subsequent welding process, thus reducing the residual stress and distortion [120, 121]. A schematic illustration of one-directional pretension is shown in Fig. 23a, in which the tension is applied in the vicinity of the weld. One-directional pretension, however, accelerates the generation of hot cracking in the transverse direction during welding. To prevent the formation of hot cracking, two-directional pretension is used (in Fig. 23b) [122]. Experiments made on 2-mm-thick 2024 Al aluminium alloy sheets showed that the distortion was gradually weakened with increasing pre-stress values. More techniques to mitigate welding-related distortions can be found in the reference [123].

4.3 Compression-integrated additive manufacturing

To reduce material distortion caused during AM, different calibration processes have been combined and integrated with the primary process. Examples are given as laser shock peening [124], shoot peening [125, 126] and rolling [127–129]. The common mechanism is that the compressive stress introduced by shock peening or rolling releases the residual stress generated during AM [113]. Here, the laser shock peening can be taken as an example, as shown in Fig. 24. During AM, residual stress is generated due to uneven temperature distribution, especially positive residual stress on the surface. The peening process, which generates

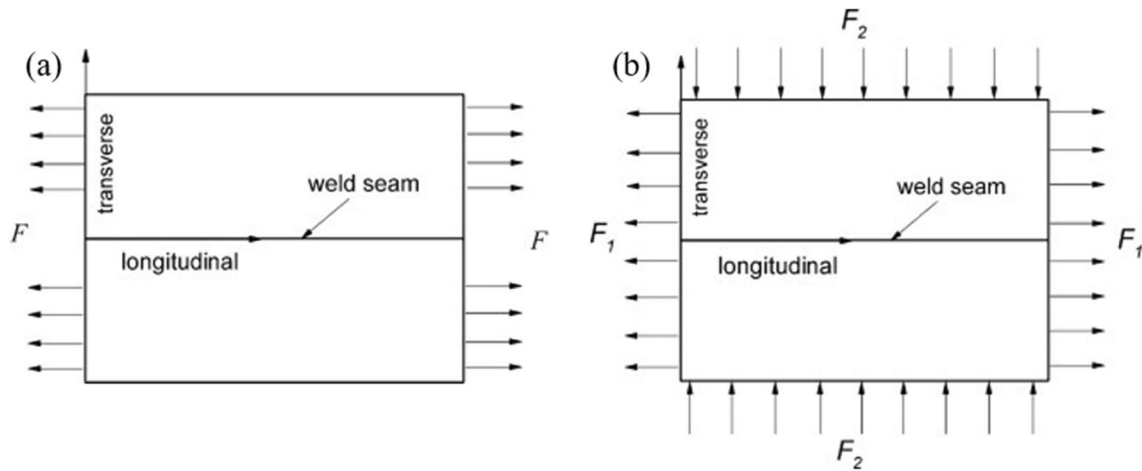**Fig. 22** Procedure of pre-bulging hydromechanical deep draw [116]

Initial state   Pre-bulging   Hydromechanical deep drawing
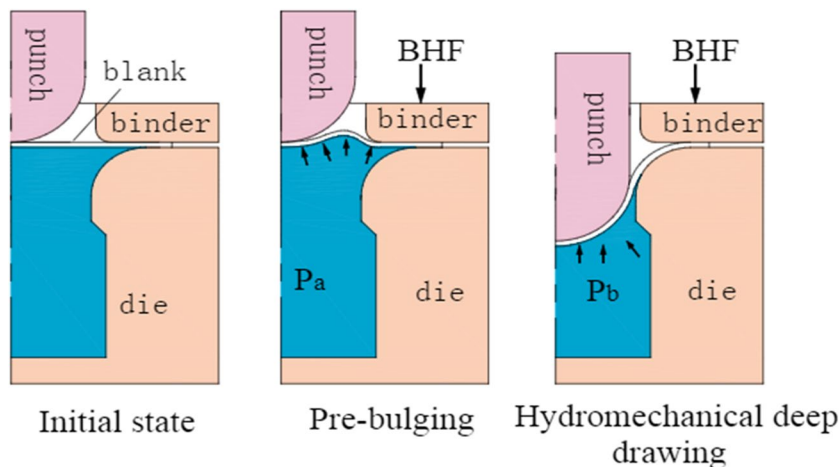
Fig. 23 Schematics of pretension models: **a** one directional and **b** two directional [122]
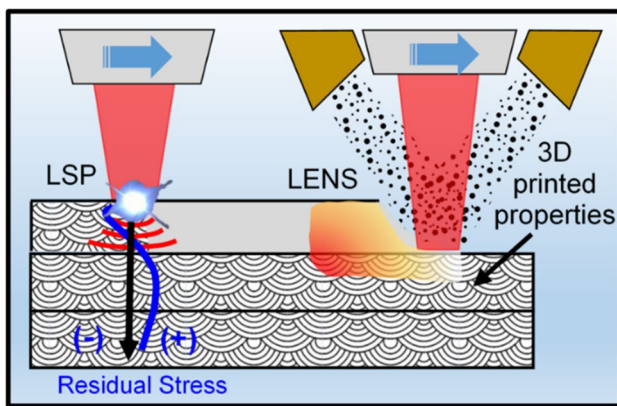

Fig. 24 Laser shock peening and AM hybrid technology [130]

compressive stresses, can offset the positive residual stress at the surface and correct distortion. The compressive deformation also hardens the materials and homogenises the material properties within different lays.

A large free-shaped metal sheet was built by AM and hot rolling integrated process. The results show high geometric accuracy, improved mechanical properties and material utilisation (in Fig. 25) [129]. It proved its capability in correcting geometric defects in thin-walled complex AMed products. More hybrid AM techniques can be found in the literature [130].

The compression-integrated AM technology corrects geometric defects by introducing plastic deformation to offset the residual stress during the primary manufacturing

Fig. 25 Large-scale component manufactured by combining AM and hot rolling: **a** 3D model and **b** physical product [129]
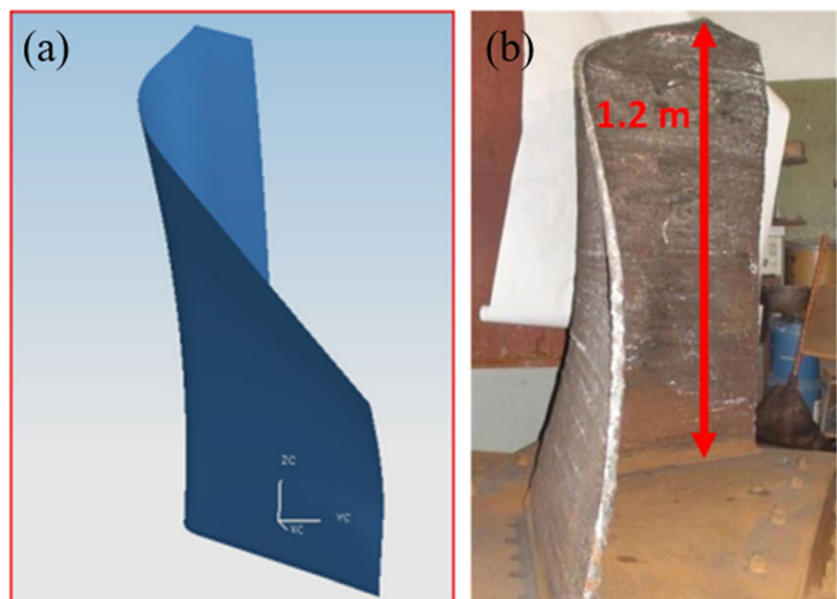
process. It requires simple tools integrated into the AM machine. It corrects the distortion immediately after the AM process from layer to layer, guaranteeing overall high material quality and low geometric distortion.

5 Discussion and outlook

This chapter summarises the state of the art of forming-based geometric correction methods. The main challenges to meeting industrial demands and scientific development will be discussed. Guidance is provided to the industry for selecting effective correction methods. Several research directions are recommended for scientific development.

5.1 Summary of forming-based geometric correction techniques

Table 1 summarises and compares the forming-based geometric correction methods described above, in terms of targeted geometric defects and their main advantages and drawbacks.

Manual correction, as the most fundamental method, has high flexibility and can be capable of most types of geometric defects. However, the high requirement for technicians with skills and experience and the long cycle time limit its use in mass production.

Mechanical correction reduces the need for manual operations and can be combined with more digital control, such as the real-time measurement of forces and geometrical configurations. The ability to use stretching, bending and compressing permits correcting a variety of geometric defects, for example, straightness, curvature and thickness inhomogeneity. However, one characteristic of the rejected products is the wide range of geometric deviations, and some may be associated with different types of geometric defects, implying that they cannot be easily corrected using one rigid machine. Digital-controlled flexible correction methods can provide possibilities. For example, in the 3D flexible rotary bending technique, the movement of the bending tools is digitally controlled along five independent freedom degrees, enabling the manufacturing of long profiles with complex curvatures [36, 131, 132]. Although it has not been used in correcting, it has a high capability for forming components with varying curvatures. Another advanced example is torque superposed spatial (TSS) bending, a roll-bending-based process with the capability to twist the profile arbitrarily [37]. It shows the potential to correct twists. The freeform forming provides more possibilities to form and correct complex tubes with digitally controlled dies [133, 134]. Incremental forming, which is highly flexible to form free-form sheets, was also used to reshape the rejected products into new products for a wider range of applications [135–137].

The high flexibility of these advanced technologies provides solutions to correct geometric defects with different sizes and shapes in both mass and customized manufacturing.

Hydraulic correction replaces the direct full die contacts in the mechanical correction with fluid-workpiece contacts. It can be integrated with the main hydroforming process or work as an independent post-forming process. In-plane stretching provided by the inner pressure can be used to remove wrinkles or waviness on thin-walled sections [53, 138]. However, forming sharp corners with high accuracy requires very high pressure. Electro-hydraulic calibration shows the capability of sharpening the corners by employing electricity-induced impulsive force [101, 102]. Hydraulic correction shows high geometric accuracy due to the stretching force caused by the inner pressure, which can reduce springback, but it requires a long cyclic time, as compared with mechanical calibration.

Electromagnetic impulse correction uses Lorentz's forces to deform parts [32]. It features as short cycle time and low springback, compared with other types of calibration methods. However, the main challenge is to understand the deformation mechanisms due to the interaction effects of the multi-physics fields, without which the deformation cannot be predicted accuracy and more errors and trials need to be done. Also, it is only applicable to metals with good magnetic conductivity.

For hard-to-deform metals, the thermal correction could be used, which can effectively avoid material fracture and reduce the springback; however, it has limited application for the complex. Usually, local heating is applied to correct the distortion caused by residual stresses. The cost of the machines is relatively inexpensive, but the precision strongly depends on the operators' experiences [30]. To achieve guaranteed high precision, the hot sizing process was developed. It deforms a part under constrains of dies at high temperatures [31]. It should be noted that this process is only appliable to products made of materials that are creep sensitive, such as aluminium alloys.

In-process correction is integrated with the primary manufacturing process, which saves time and cost because it demands simple machinery and tools such as pre-bulging in deep drawing or pre-tension in welding. Based on the actual characteristics of the geometric defects, different correction processes can be used. For example, the tangential (hoop) plastic strain formed in pre-bulging using inner pressure can offset the tangential compressive strain generated in deep drawing caused by the punch, thus mitigating the occurrence of wrinkling [116, 117]. The through-thickness compressive stress caused by hot rolling can offset the tensile residual stress generated on the surface of AMed components [129].

Overall, a large number of forming-based geometric correction methods have been developed for different kinds of components and various types of geometric defects. They

Table 1 Comparisons of forming-based geometric correction techniques

Forming-based geometric correction techniques		Targeted problems	Main advantages	Main drawbacks
Manual correction		Bending; twisting; undesired angles; buckling; dimples	High flexibility; high formability; suitable for complex products	Low time and cost efficiency; low geometric accuracy
Mechanical correction	Stretching-based correction [61–64]	Wrinkles; curvature; unevenness; warping	Low tool cost; suitable for simple geometries such as semi-finished products	Potential over-thinning or fracture
	Bending based correction [65–71, 73, 75–78]	Curvature; side curling; cross-sectional distortion	High efficiency; suitable for mass production	Large springback
	Stretch and bending hybrid correction [15, 79, 80]	Cross-sectional distortion; inaccurate gap opening	Low springback; suitable for complex geometry	Low flexibility (fixed tools)
	Compression-based correction [81–85, 88, 89]	Waviness; wrinkles; uneven thickness	High efficiency in homogenising thickness; improved surface quality	Only suitable for simple geometries
	Peening-based correction [95–98]	Curvature; waviness; poor concentricity	High flexibility to arbitrary shapes; higher surface quality	Limited capacity for tight curvature radius; hard to control the process
Hydraulic-based correction	Hydromechanical correction [50, 53, 99, 100]	Buckling; wrinkles	Good finish surface; high formability; cheap tool cost	Long cyclic time; difficulty in forming tight corners
	Electrohydraulic correction [101, 102, 104]	Curvature; wrinkles; large round corners	Good finish surface; high formability; High flexibility; higher precision	Long cyclic time; complex multi-physics mechanism; hard to control the process
Electromagnetic impulse correction [107–109]		Inaccurate angle; waviness	Good finish surface; high formability; high flexibility; high precision	Limited to small parts; high energy consumption; only appliable to conductive materials; complex multi-physics mechanism; hard to control the process
Thermal correction	Local heating [111–114]	Curvature	Good formability; low tool cost; low springback	Low repeatability; low precision accuracy; low time and cost efficiency
	Hot sizing process [31, 115]	Curvature; unevenness	Good formability; improved mechanical properties; low springback	Applicable to limited metals; super long cyclic time; high die cost
In-process correction	Pre-bulging integrated deep drawing [116–119]	Potential wrinkles and thinning	Reduced wrinkles and thinning; low tool cost; improved formability	Time-consuming; limited to specific applications
	Pre-tension integrated welding [120–123]	Curvature	Reduced residual stress; appliable for various geometries	Potential thinning and fracture; time-consuming
	Compression-integrated additive manufacturing [124–129]	Distortion	Reduced residual stress; high time efficiency; high mechanical properties; high flexibility	High tool cost; only suitable for simple geometries

have different characteristics and are suitable for different types of geometric defects. Different correction mechanisms are analysed above, which can be a guidance for industries to select the most effective methods to specific defects.

5.2 Prospect for geometric correction of complex thin-walled metallic components

There is a strong drive from the industry for thin-walled products with complexity. These products are usually associated with complex cross-sectional features with multiple inner webs and variable curvatures along the length direction. It implies the possibility for the occurrence of geometric defects and dimensional deviations with increased complexity, and the demand for more advanced geometric correction methods. However, in practice, the geometric correction techniques still focus on simple geometries and semi-finished products like tubes. To meet emerging challenges, the following future research directions are suggested:

(a) Developing correction techniques with high flexibility. For instance, single-point incremental forming is suitable for correcting a wide range of geometric defects. Multistep correction can be applied if the defect is complex and cannot be fixed within one step.

(b) Developing techniques based on generation mechanisms of geometric defects and deviations. For example, the tensile residual stress is formed on the surface of AMed parts. Thus, compression-based correction methods such as shot peening or rolling should be used to offset the initial positive stress. With more complex defects, correction techniques should be developed according to the defect generation mechanisms for high effectiveness and high geometric accuracy.

(c) Developing multi-physics-based technologies. Hydraulic correction offers homogeneous pressure and smooth surface, and electrohydraulic forming can offer higher precision with high impulsive force. The multi-physics-based technologies provide more advantages which cannot be achieved easily in mechanical calibration. It is important to further the study and have a deep understanding of these technologies such as electromagnetic impulse correction to drive the mass manufacturing of high-precision products.

High-precision and robust numerical simulation is of great importance for accurate geometric correction. Although numerical methods have been widely used in metal forming analysis, it is still challenging to predict many correction processes accurately enough. The main reason is that the workpiece after forming and ready for correction is much more complex as compared to the main forming processes from billets to parts, as well as some uncertainties prevail in terms of formed geometry, stress states and microstructure due to the complex processing history of the primary process. The main forming processes introduce inhomogeneous states of stress and strain within the workpiece [27], and also the thermal-mechanical processes would cause variations in the microstructural level such as grain size, participates and phase transformation fraction [17, 139–142]. All these factors make the final geometries of parts vary within wide ranges [17]. Thus, for higher accuracy of predictions and thus higher geometric accuracy in practice, it is necessary to study the effects of variability in initial geometries and material properties on the calibration capabilities.

In addition, in the development of the geometric calibration process, how to accurately measure the variabilities and uncertainties of the parts and further take them into account to control the process is of crucial importance. At present, measurements of manufactured parts are operated offline in most cases, which is time-consuming and makes it difficult to integrate the production lines. Effective measurement methods ensure the setting of these predicted mechanical and physical predictions [142]. For this purpose, a focus could be placed on the in situ detection and monitoring of the geometric dimensions of parts to obtain the dimensional deviation of individual parts. Furthermore, adaptive correction processes can be developed to use the in situ measurement results as an input to adaptively adjust the process parameters to correct the individual products for improving geometric accuracy [142]. Allwood et al. [17] showed examples when closed-loop control is used with the consideration of imperfection in terms of material behaviour and stochastic variations in metal forming.

Overall, the above suggestions are given to develop advanced technologies and scientific knowledge to face tomorrow's challenges in correcting geometric defects for high-precision, thin-walled metallic products.

6 Conclusions

Geometric correction plays a significant role in improving geometric accuracy and achieving defect-free products and reducing waste in manufacturing processes. Insights into the understanding of geometric correction are provided to drive the development of new geometric correction methods to face the newly emerging challenges in the manufacturing of thin-walled complex components. The following conclusions can be drawn:

(1) Geometric defects associated with thin-walled products are categorised into four types: longitudinal defects, cross-sectional defects, thickness defects and local

defects based on geometric characteristics, and the generation mechanisms were analysed.

(2) The geometric control strategies in the manufacturing chain were compared and analysed. The correction included control strategy includes post-process correction and in-process correction.

(3) The geometric correction methods in the literature are organised and discussed based on different deforming mechanisms, aimed at different geometric defects such as curvature, waviness, ovality and over-bent angles. The existing technologies were compared in terms of targeted defects, advantages and disadvantages.

(4) Research directions are suggested in developing new geometric correction techniques for new geometric defect challenges associated with complex thin-walled products and in developing robust prediction models for correction processes. Flexible and knowledge-based correction techniques should be developed for corrections in mass-volume and with high accuracy. Deformation history should be considered in the prediction model of correction processes for high accuracy predictions.

Declarations

Conflict of interest The authors declare no competing interests.

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