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Specifics of formability in recent developments of tailor welded blanks

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Abstract: This article serves as a compendium to the design engineers proceeding to manufacture geometrically complex functional components having an array of mechanical properties owing to a variety of metallic materials that are welded together. Such dynamic attempts require the knowhow of forming behavior of welded sheet metals, which are carefully explicated based on recent advances. The thickness and/or strength dissimilarity across the welded microstructures give birth to distortion and warpage in the welded sheets. The warpage during the forming operation renders the workpiece useless. The modern approaches to tackling the warpage phenomena like weld line movement and springback are highlighted with emphasis on unification of finite element, artificial neural networks, genetic algorithms, and analytical methods. This is necessary for the free form forming operations on welded sheets to provide creative edge and flexibility in design.

Significance statement

This work provides a multitude of solutions for the formability issues in free forming of tailor welded blanks through meticulous study of recently published literature. The decrease in production lead times, consumption of resources, waste generation, etc. can be simultaneously

achieved with an increase in part complexity in the manufacturing industry through the current study.

Keywords: Tailor welded blanks; warpage, weld line movement; springback; distortion; wrinkling; formability.

The advancements pertaining to materials engineering in recent decades enable the assemblies wherein each section has its desired set of physical properties based on its function in the part. Welding is the most widely preferred method of assembly due to its cost-effectiveness and simplicity. Thus, the fabrication of such components naturally involves (a) welding and (b) forming to impart the desired shape. Although the two processes can be employed in any sequence, the forming of the welded sheets generally offers several advantages like cost-effectiveness, light-weighting, and decrease in production time. The parts fabricated via welding of dissimilar materials or thickness and subsequently subjected to a forming process are known as tailor welded blanks (TWBs). The term "blank" signifies the featurelessness of the welded sheet, whereas the term "tailor" relates to the designability of imparting specific material properties to desired sections of the fabricated part. However, the microstructural and mechanical disparity between base metal and weld structure leads to warpage and distortion during forming, upon which the implementation of TWBs inherently depends. Therefore, standardized procedures like constructing forming limit diagrams (FLDs) using several tests including limiting dome height (LDH) tests are followed to establish the formability of the welded sheets.

The previous reviews concerning this topic provide valuable information about production techniques and applications [1], involved mechanics [2], and specific material behaviors [3]. However, a compilation of warpage phenomenon with the latest counteractive approaches is lacking in the available literature. Since the prior published reviews, welding and forming methodologies have also evolved, which increases the need for the current synopsizing. Thus, this work initially outlines the trends related to formability in TWBs and further elaborates upon physical and computational tools to control weld line movement and springback defects.

Intuitively, the formability of TWBs decreases with the increase in strength mismatch amongst the participating materials. This effect is generally quantified using the strength ratio (SR). A limiting strength ratio (LSR) was defined lately, to estimate the FLDs of TWBs with different SRs. The LSR is defined as the ratio of yield strength (YS) of the stronger metal to the forming limit of the weaker metal. The reason that necking begins after the ultimate tensile strength (UTS) is reached in a strain-controlled stress-strain curve can serve as a conceptual basis for the following expression of LSR [4],

$$LSR = \left[\frac{(\sigma_{YS})_B}{(\sigma_{UTS})_A}\right]_{limit}, \quad (1)$$

where $(\sigma_{YS})_B$ is the YS of stronger material B, and $(\sigma_{UTS})_A$ is the UTS of weaker material A. In parallel to the LSR, using simple mechanics, limiting thickness ratio was also derived [4].

The TWBs are commonly fabricated via laser welding. Recently, the tensile strength of laser tailor welded DP980 and 22MnB5 was found to increase by 75% upon hot forming [5]. Upon laser welding of interstitial free (IF) steel and high strength low alloy (HSLA) steel, though the failure took place on the IF side for the uniaxial tensile tests, the failure due to thinning upon deep drawing occurred on the HSLA side owing to its low mean plastic strain ratio [6]. For electron beam welded Ti TWBs having dissimilar thicknesses, a substantial effect of weld orientation on FLDs was observed due to variation in Lankford anisotropy parameters [7]. Lately, dissimilar gas metal arc welding (GMAW) of steels using an austenitic filler wire was also observed to yield appreciable formability [8]. Though, the weld nugget exhibited non-uniform deformation because of microstructural inhomogeneity.

Friction stir welding (FSW) is proving to be promising for producing Al-TWBs with appreciable formability, which is conventionally difficult. Parente et al. [9] welded dissimilar AA5182 and AA6061 and obtained the FLDs corresponding to different weld orientations to rolling directions. The transverse LDH specimen showed the least formability, whereas the longitudinal specimen showed the highest formability due to concentration of plastic deformation along the weld line, which was perpendicular to the loading direction. However, this behavior is material dependent and has been observed distinctly in steels. For tailor FSWed blanks, despite the thickness differential of 1.2 mm/1.4 mm, the flow stress and ductility of the welded zone were greater than both the thicker and thinner sides because of the fine-grained structure [10]. FSW is emerging as a process that can weld materials having tremendous mechanical dissimilarities, like Al and Cu, with significant formability of the Al-Cu TWBs [11].

The shift of the weld line towards the stronger or thicker materials arises from the stress and sequential strain localization in thinner/weaker regions. This defect is regarded as the weld line movement (WLM). Failure due to thinning and tearing, incoherent structural design, and wear in the dies occurs due to WLM. Moreover, the relatively less constrained material motion in the flange and side walls often results in wrinkling [1], as schematically illustrated in Fig. 1(a,b). A low blank holding force (BHF) leads to greater wrinkling, whereas a large BHF results in the

tearing of the sheet metal. The wrinkling phenomenon can be co-related to the uneven material draw-in from the thinner/weaker side, which can amplify due to sharp and/or excessive changes in weld-line orientation. Importantly, material draw-in profiles can be effectively simulated using finite element (FE) simulations, as shown in Fig. 1(c,d).

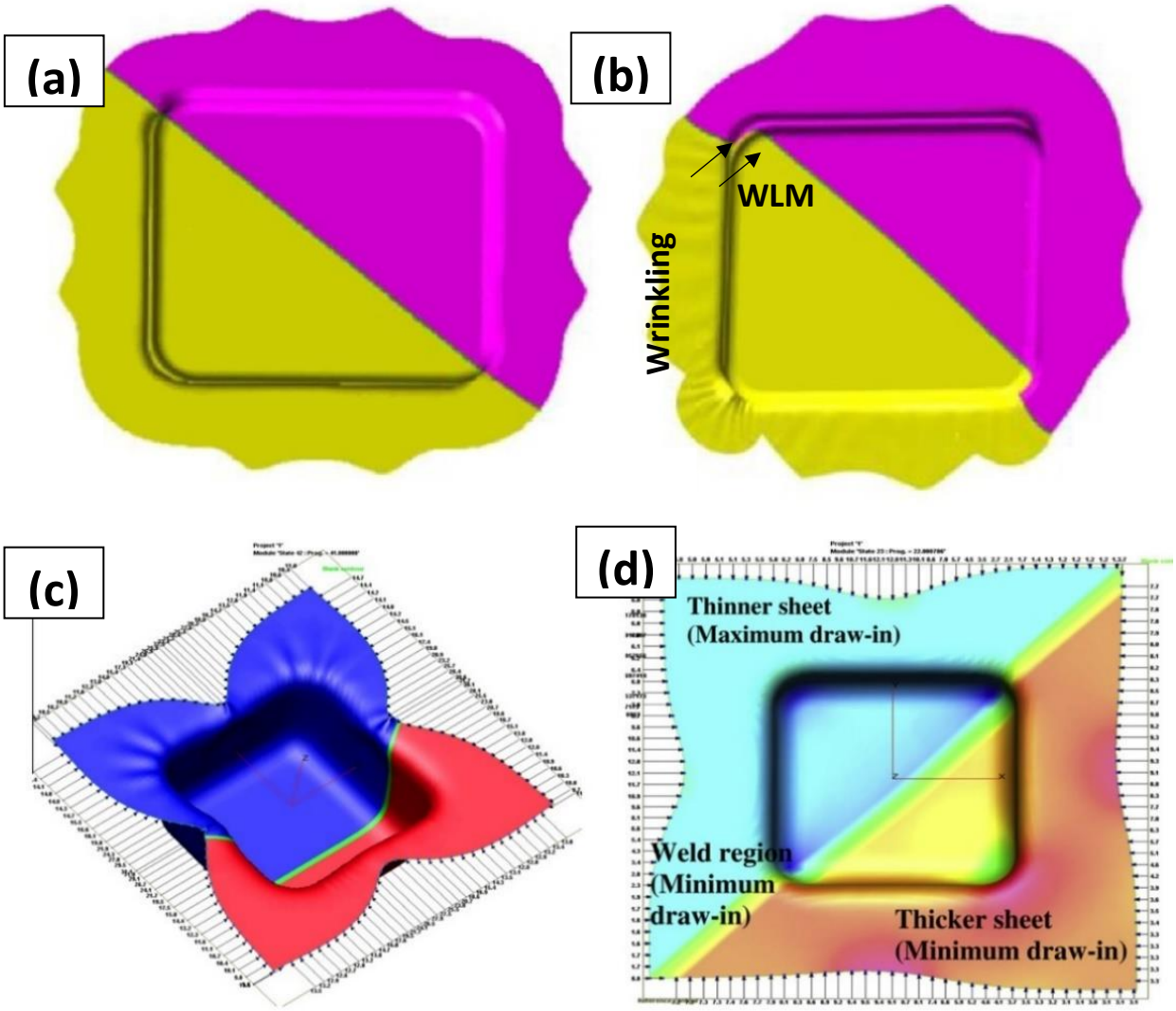

Figure-1: (a, b) Forming of a TWB: Ideal forming product with corresponding WLM and wrinkling defects [12] (c, d) FE simulations predicting the asymmetric draw-in of the TWBs in Perpendicular weld region and angular weld region [13]

Conventionally, strategies like segmented blank holder, tailored heating/cooling etc. allow decrease in WLM by controlling the holding force and associated timing. This includes a rise in the holding force at the thinner section and simultaneous decrease in the thicker side [14]. The

application of clamping pins to restrain material flow is another traditional practice. As the strength or thickness mismatch increases, a combination of such methodologies becomes important. Henceforth, researchers have also combined the two approaches experimentally achieving significant reduction in thinning [15]. The utilization of draw beads is also employed to restrict the movement of welded sheets during forming operations.

Few consolidated comprehensive frameworks are reported, that begin from material selection, proceed towards TWB design, and end in the amalgamation of reiterated FE and artificial neural networks (ANNs) to obtain final results [13]. Such usage of multiple computing techniques to formulate complex problems is termed as “soft computing”. Crucially, after TWB design, different strain hardening laws are conjugated with yield theories. Such an all-inclusive TWB formability framework is presented in Fig. 2.

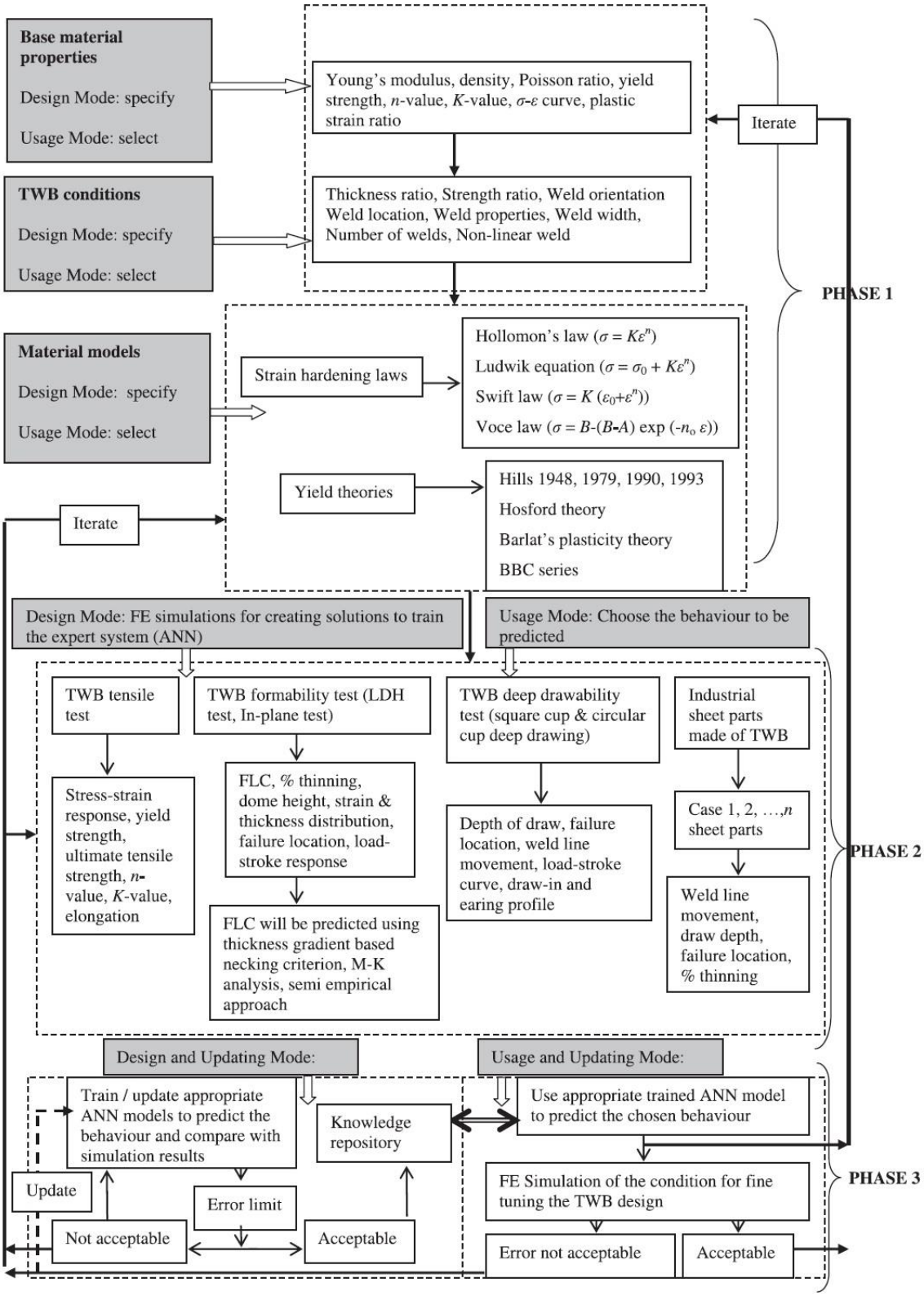

Figure-2: Formability examination framework including steps like material selection, TWB design, material behavior prediction and integration of FE analyses with ANNs [13]

In another approach, Suresh et al. [16] developed a special split punch wherein the thicker/stronger material could be heated using one part and the thinner/weaker counterpart could be cooled by supplying coolant like iced water. The objective was to balance the flow stress on both sides of the weld using temperature adjustment.

In TWBs, the thicker/stronger material undergoes smaller plastic deformation than its thinner/weaker counterpart, thus being more vulnerable to elastic recovery post the removal of the forming forces. However, compensations in tooling are effective in reduction of the springback. Conventionally, only standard geometries like cylindrical tooling, U-bends, V-bends, L-bands, etc., were investigated for the springback effect [17]. Thus, consideration and tooling compensation for springback at industrial level remained largely dependent on the experience of design engineers, leading to multiple trials before achieving set part dimensions and tolerance values. In recent years, springback behavior in complex parts was scrutinized. FE methodology is a fundamental step to compute the springback compensations in free forming parts. Of late, the following algorithm was utilized to evaluate the springback compensation [18],

$$\vec{C}^t = \vec{C}^{t-1} + a(\vec{S}^t - \vec{R}), \tag{2}$$

$$\left| \vec{S}^t - \vec{R} \right|_{max} < \varepsilon, \tag{3}$$

where $\vec{C}^t$ represents compensation shape in the tth time, a is compensation factor, varying between -2.5 and -1, $\vec{R}$ is reference shape as per design, $\vec{S}^t$ is springback shape evaluated via t^{th} FEM analysis, and ε is the component tolerance.

The precise springback estimation requires nonlinear elastic recovery to be accounted in FE analyses, which needs higher computational power. The presence of dissimilar microstructure in weld nugget and heat-affected zones highly obscures the formulations. Whilst springback depends upon numerous physical parameters, identification of the cause of misfit between predicted FEM springback and experimental recovery is challenging. Thus, ANNs are often integrated with FE simulations to minimize the incongruency between numerical and experimental results [19]. However, most initial studies concerned with the integration of ANN and FEM largely optimized the FE simulation parameters itself, leaving a rift between the actual experimentation and software

procedures [20]. Thus, the resulting compensations can largely reflect FE code response, instead of revealing true response of the deforming material. To overcome this shortcoming, an ANN based feedforward model was implanted in the user-defined subroutine to impart the actual state of material [20]. Of course, the aforementioned progress shall be extended from sheet metals to TWBs to reduce the springback effect in free forming operations.

Few analytical/semi-analytical models to predict springback of welded pipes have also been formulated. Zhan et al. [21] interestingly pointed out that the conventional analytical idea was based on the springback being equal in magnitude and opposite in sign to the bending moment, whereas the presence of residual stress makes the springback moment differ in magnitude to the actual bending moment. As thickness incongruity or SR increases, it becomes more arduous to neutralize the springback. In this direction, Nguyen et al. [22] have successfully utilized genetic algorithm-based scheme to obtain the varied blank holding force stroke profiles. Their work serves as another example of "soft computing" approach utilized to minimalize experimentation and time-intensive analyses.

With advancements in computer aided design (CAD), computer aided inspection (CAI) has also begun to be employed to map distortion in aluminum sheet metals on the basis of point cloud metrology [23]. Recently, such a real-time CAI-based approach was applied to demonstrate the distortions in laser-welded blanks using 3D laser scanners by Aminzadeh et al. [24]. As articulated in Fig. 3, the distortions due to welding and forming were measured by laser 3D scanning after both automated operations. In each of the welding and forming inspections, the rejected parts can be sent for recycling. Although FE simulations of laser TWBs are computationally demanding, approaches like volumetric heat flows are being implemented to eliminate the prerequisites like fluid flow considerations [25]. The shapes and dimensional measurements of the volumetric heat flows can be determined, based upon actual weld pool geometries obtained from the macrostructure, which enhances the accuracy of such models.

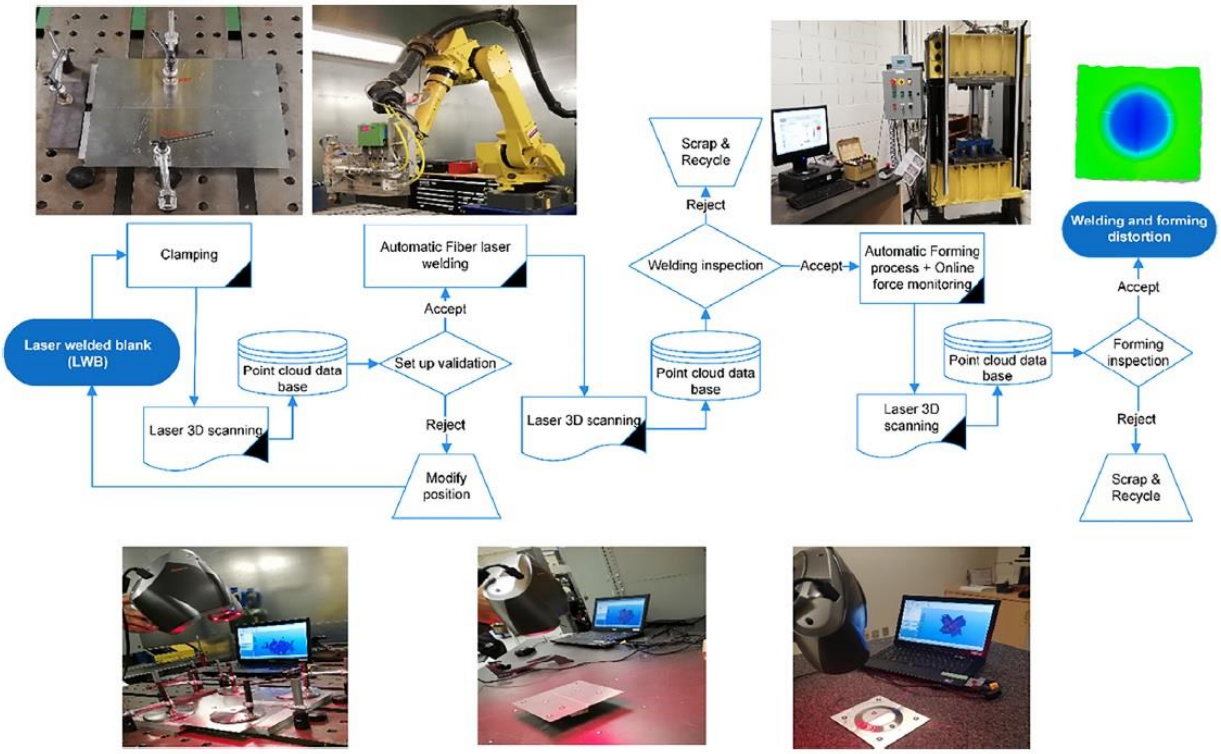

Figure-3: CAI-based distortion measurements in laser welded blanks [24]

In summary, the applicability of analytical, numerical FEM, ANN, and genetic algorithm-based approaches is expanding to control the warpage in TWBs. The WLM chiefly stems from process selection and design for free forming of welded sheets. A trade-off exists between decrease in springback effect and nucleation of forming defects. The understanding and correction of springback are complicated due to the non-linear elastic recovery of metallic materials. The springback effect chiefly depends upon the material characteristics and selection for TWBs.

The latest research in controlling defects in TWBs emphasizes on integration of neural networks with FE methods and expansion of CAD to CAI. The usage of volumetric heat sources is budding to improve the results from FE methods. On the other hand, the former research focused more on the physical methods including segmented blank holders and selective heating to control the WLM. The traditional ways to control springback included tool compensation based on engineer's experience, whereas FE methods are progressively being implemented for compensation. Furthermore, combinations of physical methods are being implemented nowadays for a decrease in distortion. The advances in FSW are playing a key role to enhance the formability of TWBs, which were traditionally produced primarily using laser welding and mash seam welding.

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The authors declare no conflicting interest.

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The article does not involve any animal/living subjects and do not require ethical committee clearance.