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RESEARCH ARTICLE

Influence of Forming Forces on Torsional, Tensile, and Compressive Deformation of Paperboard Packages

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ABSTRACT *Paperboard packages were tested mechanically to investigate influence of forming forces on torsional, tensile, and compressive deformation. The packages were paperboard trays which were press formed with different pressing forces and blank holder forces. Deformation of the trays was observed with torsion, compression, and tensile tests. A statistical analysis of test results was conducted to derive optimal forming forces. Increased pressing force yielded desirable deformation characteristics with the trays. Blank holder force had largest impact on the compressive deformation. Interaction of the pressing force and the blank holder force influenced the torsional and the compressive deformation. The optimal forming forces changed compression force of the trays by +38.2%, tensile force by +4.9%, and torsion angle by -5.4% in comparison to mean of the test results. Effects of the forming forces on microscale changes in the material were discussed. Optimisation of the forming forces was concluded to enhance strength, stiffness, and usability of the trays.*

KEY WORDS Tray, strength, stiffness, optimisation, rigidification

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INTRODUCTION

Paperboard is a commonly used biomaterial in many package formats such as trays, cups, and boxes. Trays can utilise polymer-coated paperboard to provide sufficient barrier properties for their use as food containers. Press forming is one widely used method for manufacturing paperboard trays. The press forming of trays is done by pushing a pre-cut and pre-creased blank of a tray into a cavity with a punch whilst controlling folding and sliding of the blank with a blank holder. Forming forces involved during the press forming of trays include pressing force and blank holder force. The forming forces enable stretching of the blank into a deeper shape and formation of flange region. Application of the forming forces during the press forming is visualised in Fig. 1.

Excess straining of the blank can cause ruptures in corners and walls of the tray, yet a sufficiently high pressing force and blank holder force is needed to obtain a desirable rigidity and visual quality with the press formed trays [2]. Excess friction between the blank and the blank holder can also cause ruptures and the material-tool friction has a major impact on shape of the press formed trays [3]. Besides the forming forces, forming behaviour of paperboard was closely linked to its moisture content and forming temperature by Groche and Huttel [4] and bending stiffness of paperboard by Kajanto [5]. Increased moisture content of paperboard is beneficial to its forming limits, as observed by Stein et al. [6]. In Vishtal et al. [7] the positive effect of increased moisture content on formability of paperboard was linked to a softening effect on fibres of the material. In Stein et al. [6] the

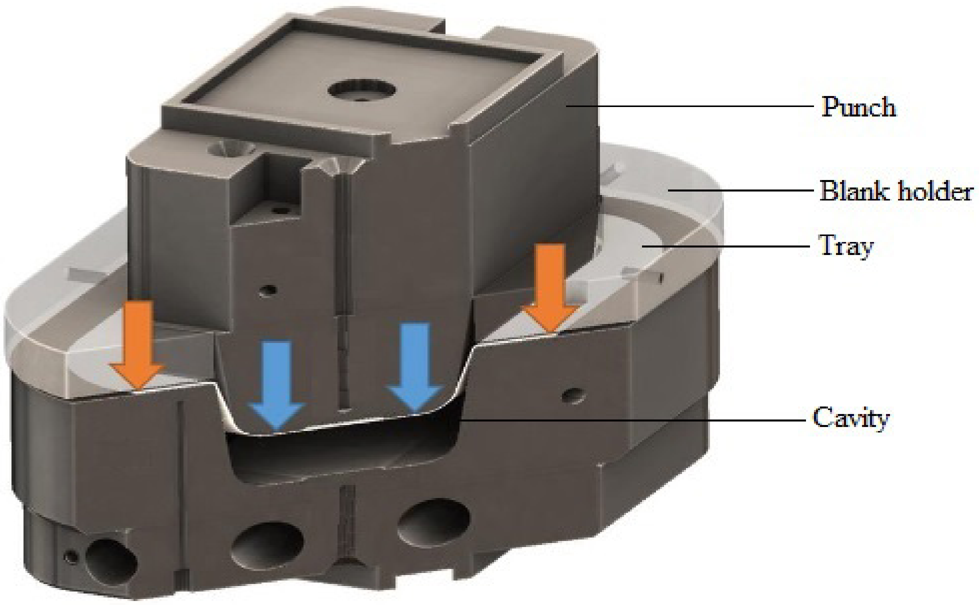

Fig. 1: Application of pressing force (blue arrows) and blank holder force (orange arrows) in press forming of a tray, modified from Tanninen et al. [1].

increased forming limit of moister paperboard was associated with reduced strength of fibre network and breakage of the fibre bonds.

Composition and fibre properties of paperboard can have major influences on its forming behaviour according to Hauptmann et al. [8]. They found that pore volume of paperboard and fibre-to-fibre mobility in the material influenced visual quality of formed paperboard shapes. Weakened top ply of paperboard was connected to increased ruptures by Lindberg and Kulachenko [9], and accordingly adjusted ply properties of paperboard were consequently related to improved material performance in the press forming of trays. Application of gelatine and agar additives had a major positive influence on three-dimensional thermoforming of paper trays in an earlier work by Vishtal et al. [10]. In Franke et al. [11] forming performance of paperboard in the press forming of trays similarly improved after application of water, gelatin, and soap additives.

The forming forces can be adjusted to reduce rupturing of paperboard during a forming cycle. A constant blank holder force provides acceptable quality with the press formed trays, and an optimally distributed pressing force is derived when 20% of the pressing force is applied on bottom of the tray while 80% of the pressing force is applied on flange of the tray [12]. In Hauptmann et al. [13] the blank holder force was adapted to reduce rupturing tendency in deep drawing of paperboard and trajectory of the blank holder force was optimised to improve visual quality of deep drawn paperboard shapes. In Müller et al. [14] increased blank holder forces were shown to produce fine and evenly distributed wrinkling in deep drawn paperboard cups and the desirable wrinkling of the material improved quality level of the cups. Quality of press formed paperboard trays can be evaluated with dimensional accuracy, yet both the pressing force and the blank holder force have only a minor effect on outer dimensions of the trays [15].

Research about role of forming forces on deformation characteristics of paperboard packages is limited. Higher blank holder forces improved tensile deformation of deep drawn paperboard shapes and increased compression of blank during the deep drawing was associated with positive effects on hydrogen bonding in the material in another work by Hauptmann et al. [16]. Tensile deformation of press formed paperboard trays has not been tested before. Studies about effects of forming conditions on compressive and torsional deformation of press formed paperboard trays have focused on forming temperature and time [17], [18]. Improved deformation characteristics of paperboard packages are closely linked to their enhanced strength and stiffness properties [16], [17], [18]. Rigidification of paperboard trays during the press forming can be facilitated by optimisation of the forming conditions and the trays with increased rigidity in turn yield a superior response to their compressive and torsional deformation [19]. In addition, dimensional instability of press formed paperboard trays in high or cyclic humidity environment can be slowed with optimised forming conditions [20].

Handling and usage of paperboard packages require a sufficient stacking performance, structural strength, and functionality in packaging lines. Stacking performance, structural strength, and functionality of paperboard packages are related to their deformation characteristics. Influence of forming forces on torsional, tensile, and compressive deformation of paperboard packages was investigated in this work. The experimented packages were press formed paperboard trays and the studied forming forces consisted of pressing force and blank holder force. The trays were press formed with different pressing forces and blank holder forces. Torsion, tensile, and compression tests were conducted to observe the deformation of the trays. Optimal forming forces were derived with a statistical analysis of test results. Optimisation of forming forces is needed to obtain paperboard packages with desirable deformation characteristics. Enhanced strength and stiffness properties of press formed paperboard trays can be moreover exploited to enable wider and more durable usage of paperboard packages.

MATERIALS AND METHODS

Materials

A commercial paperboard material with a polyethylene terephthalate (PET) coating was used to manufacture the tested packages. Baseboard of the material consists of a chemi-thermomechanical pulp (CTMP) middle layer and solid bleached sulphate (SBS) outer layers. Grammage of the baseboard is 350 g/m^2 and grammage of the coating is 40 g/m^2. Thickness of the material is 480 µm. The material was stored at 50% relative humidity (RH) and 23 °C before the packages were manufactured. Moisture content of baseboard of the stored material was 8 ± 0.4% as calculated by weighting oven-dried blanks of the trays according to ISO 638-1 [21].

Packages

The studied packages were standard Gastronorm (GN) ¼ trays. Dimensions of the GN ¼ tray are 265 mm x 162 mm x 38 mm, and the tray geometry is commonly used as a food container. Longer side of the tray was aligned parallel to machine direction (MD) of the material. Manufacturing of the packages included die cutting of blanks of the trays and press forming of the trays. Blanks of the trays were creased and cut with a *Ruiyang ML1200* flatbed die cutter (Ruian City, China). The trays were press formed with a forming module of *LUT Packaging Line* (Lappeenranta, Finland). Press forming conditions were adjusted to correspond to a production run with a speed of 24 trays per minute. The following press forming conditions were used: unheated punch, cavity temperature 150 °C, dwell time 1 s, and pressing speed 80 mm/s. Three different pressing forces (15 kN, 75 kN, and 150 kN) and blank holder forces (0.75 kN, 1.5 kN, and 3.0 kN) were selected. The highest pressing force was a maximum pressing force of the utilised forming module. A pressing force below 15 kN produced trays with insufficient quality by a visual analysis, therefore the three pressing force levels were distributed evenly between 15 kN and 150 kN. A blank holder force above 3.0 kN caused ruptures during the press forming and a maximum blank holder force was thereby limited to 3.0 kN. The other blank holder force levels were distributed evenly.

Testing and validation

Deformation of the packages during their handling, usage, and stacking was evaluated and simulated with torsion, tensile, and compression tests. The tests were conducted with a minimal delay after press forming of the trays. The torsion tests involved clamping shorter sides of a tray to *LUT tray stiffness tester* (Lappeenranta, Finland)

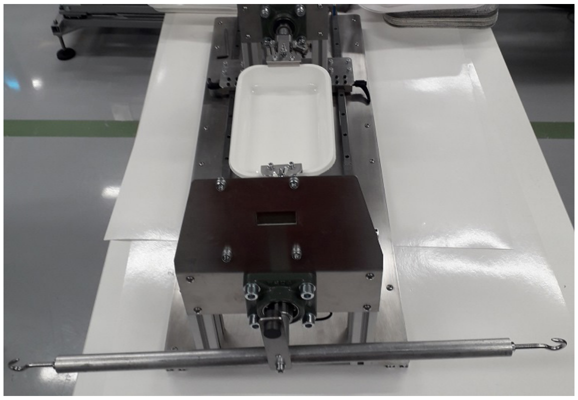

Fig. 2: LUT tray stiffness tester.

and twisting the clamped tray clockwise and counterclockwise with weights which caused a 0.036 Nm torsional load. Torsion angle of the tray was obtained from an angular measurement system of the tray stiffness tester and the measured torsion angle was used to indicate torsional stiffness of the tray. The utilised tray stiffness tester, depicted in Fig. 2, was presented in detail in a previous work by Tanninen et al [18].

The tensile and the compression tests were conducted with a *Shimadzu AGS-10kNX* universal tester (Kyoto, Japan). Accuracy of the tester is ± 1% for measured force values. Due to anisotropic nature of paperboard, the tensile testing was confined to cross direction (CD) of the material. Longer sides of a tray were clamped to the tester for the tensile test, as displayed in Fig. 3. Clamp distance was 162 mm and clamp size 25 mm. Tensile test speed was 100 mm/min and break detection sensitivity was a 10% drop in the measured tensile force. In the compression test a tray was compressed between two metal plates to reduce height of the tray by 12 mm. Compression test speed was 100 mm/min. Setup of the compression tests can be seen in Fig. 4. Reported test results are an average of six trays. A statistical analysis of the test results was performed with MATLAB software using a multiple linear regression with interaction. Significance of the forming forces and their interaction was interpreted with *P*-values.

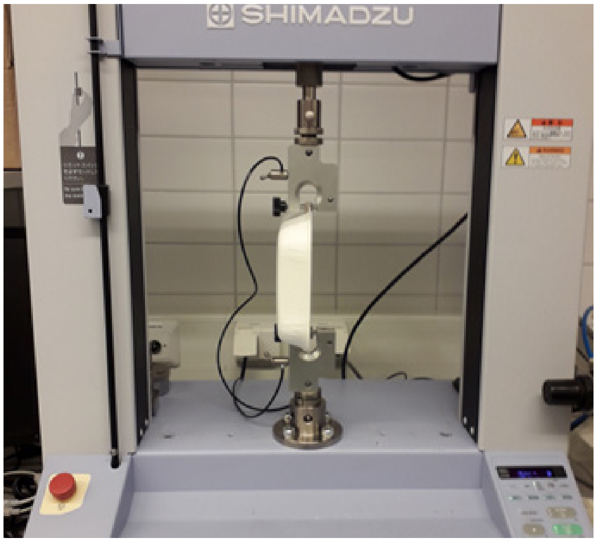

Fig. 3: Tensile test setup.

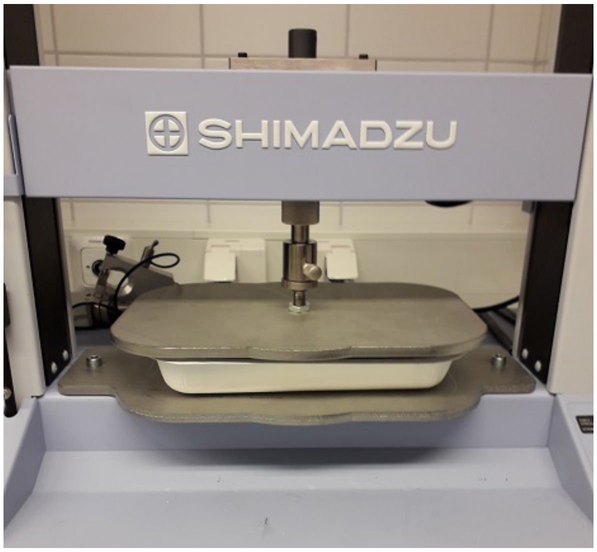

Fig. 4: Compression test setup.

RESULTS AND DISCUSSION

Pressing force had a major effect on torsion angle of the trays. Blank holder force had only a minor effect on the torsion angle. Torsion test results are outlined in Fig. 5.

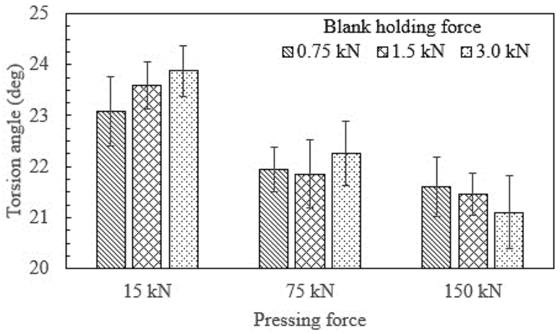

Fig. 5: Torsion test results, standard deviation is indicated with error bars.

The maximum pressing force increased tensile force of the trays. The maximum pressing force combined with the minimum blank holder force had a minor positive effect on the tensile force. Tensile test results are detailed in Fig. 6.

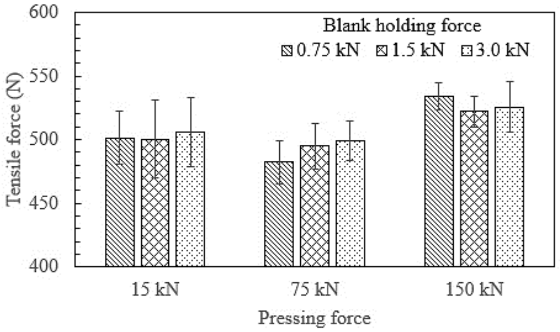

Fig. 6: Tensile test results, standard deviation is indicated with error bars.

Pressing force had a clear effect on compression force of the trays. Blank holder force had a larger effect on the compression force when the pressing force of the trays was 150 kN. Compression test results are shown in Fig. 7.

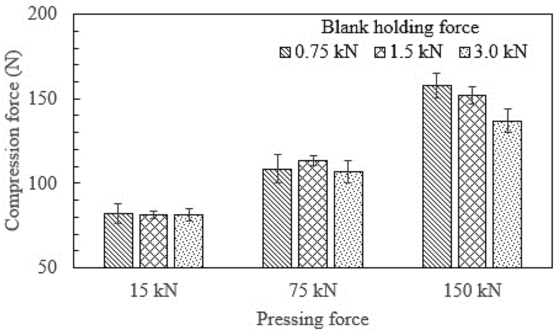

Fig. 7: Compression test results, standard deviation is indicated with error bars.

A statistical analysis of the test results validated significance of the pressing force to the torsion angle and the tensile force of the trays. Interaction of the pressing force and the blank holder force was significant to the torsion angle, as displayed in Fig. 8. The interaction was not significant to the tensile force. Statistical analysis of the tensile test results is depicted in Fig. 9. The pressing force, the blank holder force, and their interaction were all significant to the compression force. Statistical analysis of the compression test results is provided in Fig. 10.

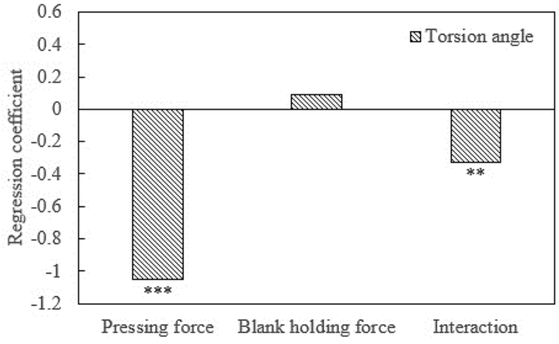

Fig. 8: Statistical analysis of torsion test results, significance is highlighted with asterisks.

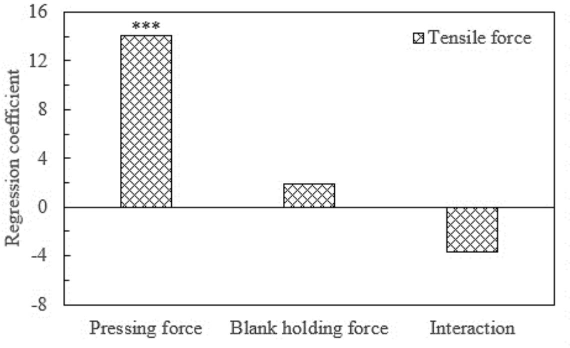

Fig. 9: Statistical analysis of tensile test results, significance is highlighted with asterisks.

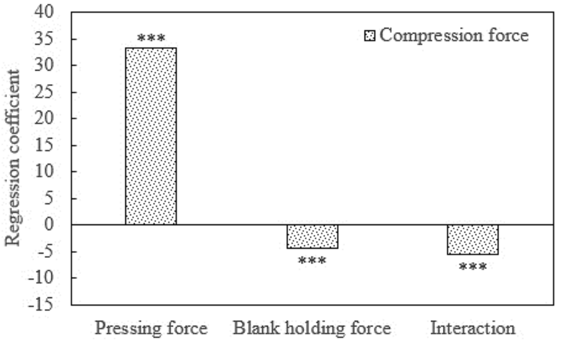

Fig. 10: Statistical analysis of compression test results, significance is highlighted with asterisks.

Highest tensile and compression forces were obtained with the trays press formed with 150 kN pressing force and 0.75 kN blank holder force. Lowest torsion angle was obtained instead with the trays press formed with 150 kN pressing force and 3.0 kN blank holder force. Optimal forming forces increased the compression force of the trays by 38.2% in contrast to mean value of the test results. Using the same comparison, the tensile force was increased by 4.9% and the torsion angle was decreased by 5.4%.

Strength of paperboard is strongly affected by ability of fibre network to transfer stress concentrations to fibres and rigidification or softening of the fibres heavily influences the ability to transfer stress concentrations in the fibre network [22]. Weakening or strengthening of fibre-to-fibre bonds affects the strength of paperboard [22], as does a change in number of fibre-to-fibre bonds [23]. Microscale changes in fibre network influence mechanical properties of paperboard such as tensile strength and bending stiffness [24], consequently the possible effects of blank holder force and pressing force on the microscale changes should be discussed.

Hydrogen bonds can form when wet fibres are pressed against each other and simultaneously dried [25]. Water bridges between the pressed fibres facilitate the formation of hydrogen bonds [26]. During the press forming the punch presses the moist paperboard blank against the heated cavity while the blank holder presses the flange region of the blank against the cavity. As a result, fibres in the material are pressed against each other and dried. Fibres in the material additionally shrink and become less extendable when they are dried [6]. The forming forces can be ascribed to facilitate hydrogen bonding in the material by pressing the fibres closer while heat input from the cavity to the pressed fibres enhances their rigidification by drying. The optimal forming forces were consequently suggested to improve strength and stiffness of the trays by increasing rigidity of fibres and number of hydrogen bonds in fibre network.

Defect formation during tensile deformation of paperboard can occur in its thinner or less dense regions [27]. The pressing force is largely confined to bottom and walls of the tray [12]. The blank holder force is confined to flange of the tray and an increased blank holder force produces a flatter flange [12]. Break initiation in the tensile tests occurred next to clamped parts of the trays. Observed breaks in a tensile tested tray are shown in Fig. 11. Compression of the trays flattened walls of the trays and bent flange of the trays, as highlighted in Fig. 12.

Fig. 11: Detected breaks in a tensile tested tray observed from bottom (left) and top (right) of the tray, the breaks are highlighted with arrows.

Fig. 12: A visual comparison between a compressed tray (left) and an uncompressed tray (right).

The observed defects during the tensile deformation of the trays were connected to a thinner region of the material on the flange of the trays and stress concentrations around the clamped parts of the flange. Bending stiffness of the trays with a flatter flange was moreover linked to the compressive deformation.

Bending stiffness, compression strength, and thickness of paperboard have a linear relation [28]. The trays press formed with 150 kN pressing force and 3.0 kN blank holder force had a slightly smaller compression force than the trays press formed with 150 kN pressing force and 0.75 kN blank holder force. Compressive deformation of the trays occurred partly via bending of the flange of the trays. The compression test results indicated that the trays with a flatter flange had a reduced bending stiffness. The finding was evident with the trays which were press formed with the maximum pressing force. This could be due to larger microscale changes in the material which became observable once the maximum pressing force was used. The statistical analysis of the test results in addition validated that the blank holder force was a significant variable to the compressive deformation of the trays, but not to the torsional and the tensile compression.

The torsion test results indicated that the trays with a flatter flange did not have a reduced torsional stiffness. Thickness asymmetry in paperboard does not have a strong effect on torsional stiffness according to Hernández-Pérez et al. [29]. The torsion test results depicted similar findings since the blank holder force and its interaction with the pressing force had only minor effects on the torsion angle. The discussed microscale effects in the material can be nonetheless considered positive for the torsional deformation of the trays due to a linear decrease of the torsion angle against the increased pressing force.

The maximum pressing force provided desirable deformation characteristics with the tested packages. Torsional stiffness, tensile strength, and compression strength of the packages were improved when the forming forces were optimised. The enhanced strength and stiffness of paperboard trays press formed with the optimal forming forces enable wider usage as the trays can sustain larger external forces from their handling and stacking. However, deformation characteristics of paperboard packages can be also influenced by other conditions such as moisture content, coating, thickness of the material, forming temperature and time, and sealing of the packages [7], [17] - [20]. The other conditions can similarly limit the selection of the forming forces. The selection of the forming forces should consequently account usage requirements of the packages.

CONCLUSIONS

Optimisation of forming forces had a positive effect on torsional, tensile, and compressive deformation of paperboard packages. The packages consisting of press formed paperboard trays showed superior deformation characteristics when a maximum pressing force was utilised. Blank holder force had a more limited effect on the deformation of the trays.

Increased pressing force values were linked to improved torsional stiffness, tensile strength, and compression strength of the trays. A high pressing force in press forming of paperboard trays is beneficial for rigidity of the trays and the benefits from the use of high pressing force were associated with positive microscale changes in the material. The discussed microscale changes were related to rigidification of fibres and increase of hydrogen bonds in the material.

The blank holder force is confined to flange of the tray during the press forming and therefore the effects of different blank holder forces were less observable when walls of the trays were deformed. The blank holder force should be optimised despite its limitations since interaction of the pressing force and the blank holder force affected the torsional and the compressive deformation of the trays and an excess blank holder force can cause ruptures during the press forming.

Improved deformation characteristics of paperboard packages facilitate their usability, and the optimal forming forces outlined in this work can be exploited to press form more durable paperboard trays. The objective to obtain paperboard packages with desirable deformation characteristics was achieved. Compression test results of the trays help to quantify how much higher stacking performance can be acquired when the forming forces are optimised.

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