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An Experimental Investigation of the Effect of Compression Calibration on the Ductility of AA6061 Extrusions

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Abstract. The growing use of extruded aluminum components in vehicle structures necessitates both strength and ductility to meet energy absorption requirements. In this study, a new compression calibration method for multi-chamber, hollow sections was developed with the aim of improving dimensional accuracy while enhancing the ductility of AA6061 extruded profiles. The influence of this method on mechanical properties was investigated through uniaxial tensile tests, three-point VDA bending tests, and axial crush tests. The uniaxial tensile test results revealed a reduction in the (logarithmic) strain at necking, while no significant changes were observed in yield and ultimate tensile strengths. On the other hand, the VDA tests showed a systematic increase in the normalized bending angle, indicating improved energy absorption characteristics. Visual inspection and the absorbed energy obtained by axial crush tests supported the findings in the VDA tests, indicating the compression calibration method enhances the crushability of extruded AA6061 profiles, although this improvement is not identified in standard tensile data. Overall, this work introduces a new, industrial calibration method for hollow extrusions that also enhances crushability.

Introduction

In manufacturing operations, mechanical calibration strategies are sometimes employed after extrusion to achieve the dimensional accuracy required for subsequent manufacturing steps or the fit-up of the final product. Many of these methods apply controlled plastic deformation to induce permanent shape correction, thereby eliminating geometrical distortions and imperfections occurring during the extrusion process. A very common example is post-stretching—also referred to as straightening—immediately after extrusion, which has become an integral part of modern extrusion production lines. Calibration can also be performed as an individual, secondary manufacturing operation downstream from extrusion. Møretrø et al. [1] provided a comprehensive comparison of different mechanical calibration methods, highlighting the capability of each method for correcting different types of geometrical imperfections occurring during the extrusion process. Welo et al. [2] investigated a new calibration method for open U-section extruded aluminum profiles, which combines the principles of stretching and bending. This approach reduces springback and consequently improves the dimensional accuracy of the profiles.

Although improving geometric stability through mechanical calibration comes at an additional cost, it may also provide improved mechanical properties of the final product for specific aluminum alloys. Qvale et al. [3] investigated how varying pre-stretching levels (0.5% and 4%) affect the strength and ductility of extruded double-chamber AA6063 and AA6082 profiles. Similarly, Granum et al. [4] examined the effect of pre-stretching on the ductility of rectangular hollow AA6063, AA6061, and AA6110 profiles. The uniaxial tensile test results from both studies demonstrated that increasing the pre-stretch level from 0.5% to 4% improved ductility. In addition, profiles pre-stretched to 4% showed fewer cracks after quasi-static crush tests, confirming the positive impact of plastic deformation on ductility. Qvale et al. [3] also noted that the improvement in ductility due to pre-stretching was more pronounced for AA6063 than for AA6082, as determined from both uniaxial tensile tests and inspection of crack formation observed during quasi-static tests. Built on the stretching method, Leśniak et al. [5] developed a semi-industrial prototype capable of applying dynamic stretching at higher speeds to extruded rectangular hollow AlMgSi(Cu) profiles. The results showed that the dynamically stretched profiles exhibited a fine-grained and homogeneous microstructure, providing improved mechanical strength and dimensional tolerances within acceptable limits. In their subsequent study, however, Leśniak et al. [6] reported that dynamic stretching led to a noticeable reduction in the ductility. Overall, these studies show that the influence of calibration processes on ductility strongly depends on both the material composition and the type of calibration method employed.

While ‘ductility’—often determined from stress-strain characteristics obtained from uniaxial tensile testing—is a significant parameter for assessing the crash performance of extrusion-based vehicle components, its proper evaluation requires careful selection of appropriate test methods. Victor et al. [7] stated that although a standard tensile test provides reliable information regarding the strength of a material, elongation (strain at fracture) used as an indicator of ductility is not an accurate indicator of the material’s deformation capability in practice. Parson et al. [8] investigated the influence of temper condition on the crush behavior of several 6xxx series alloys, reporting that yield strength alone is not a unique indicator of crash performance and the existence of a linear relationship between ultimate tensile strength and absorbed energy. Therefore, alternative methods for assessing ductility, such as bending tests and axial and transverse crush tests, are commonly used. The potential and limitations of the VDA bending test, which has become the standard in the automotive industry for evaluating the ductility of extrusion-based vehicle components, have been widely discussed in the literature. According to Parson et al. [9], the VDA bending test suppresses necking and promotes surface-initiated failure, thereby replicating real-world deformation mechanisms that occur under lateral or axial crushing. Similarly, Victor et al. [7] emphasized that the VDA bending test provides a more accurate measure of a material’s resistance to damage and thus its overall energy absorption capability. As a result, the VDA test is commonly used to evaluate ductility using the normalized bending angle as an indicator of the material’s deformation capacity. Unlike the VDA bending test—which focuses on local surface deformation—the axial crush test represents an alternative way of evaluating ductility at the component level by characterizing the global deformation behavior under a state of crushing. The total absorbed energy, energy absorption efficiency, and crack inspection are used to assess ductility (or better crushability).

Although mechanical calibration methods have been studied from the viewpoint of effects on dimensional accuracy and overall mechanical response, their influence on ductility, which is essential for real-world impact behavior of vehicle components, has rarely been addressed in the literature. In this study, an innovative compression calibration method was developed to improve the dimensional accuracy of complex hollow profiles. In this connection, it is also of primary interest to investigate how the deformation process impacts the mechanical performance of the calibrated component. This calibration method—designed for extruded multi-chamber hollow profiles—compresses all exterior surfaces of the profile using internal mandrels and external mechanical tools. The effects of the method on strength and ductility have been evaluated by comparing calibrated and uncalibrated AA6061 profiles through uniaxial tensile tests, VDA bending tests, and axial crush tests. Moreover, the extraction of test specimens from different regions of the profile allowed the evaluation of the influence of extrusion seam welds and material orientation, which are both known to impact ductility.

A new compression calibration technique

In the compression calibration stage, a lubricant is first applied to the inner surface of the profile, after which an inner mandrel is inserted into the profile. The lubricant ensures uniform friction and allows the mandrel to be removed easily after deformation. The inner mandrel was specifically designed for double-chamber hollow profiles and additionally provides uniform support to the surfaces. The profile is then compressed uniformly from all four sides under a total compression force of approximately 200 tons. The tooling configuration and the corresponding compression kinematics are schematically illustrated in Fig. 1a. The compression calibration method applied in this study follows the general principles described in the patent by Paulsen et al. [10], which covers the use of internal mandrels and external dies for the calibration of multi-chamber hollow profiles.

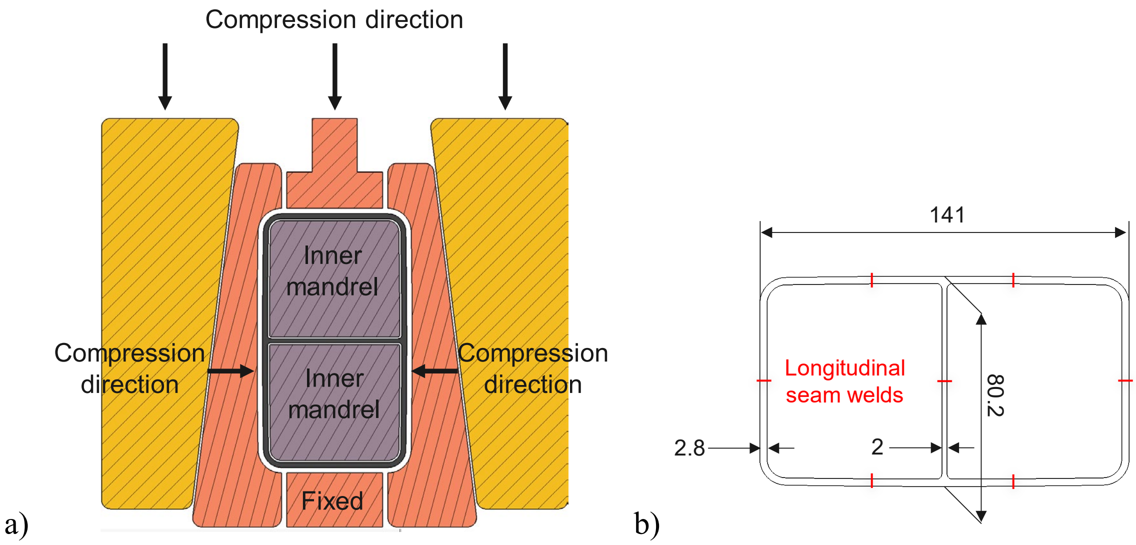


Fig 1. a) Schematic of the compression calibration setup and tool movement directions **b)** Sketch of the multi-chamber hollow aluminum profile and longitudinal seam weld positions

Material

Double-chamber hollow AA6061 profiles extruded by Benteler Automotive, Raufoss (Norway), were used in this study, as shown in Fig. 1b. The chemical composition of the billet is listed in Table 1. Before calibration, the profiles were solution heat-treated at 570 °C and subsequently water-quenched. After calibration, the profiles were subjected to stabilization at 150 °C for 30 minutes and then artificially aged at 190 °C for 4 hours to obtain the desired mechanical properties.

Table 1. Chemical composition of AA6061 in weight%

6061	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
	0.66	0.19	0.10	0.02	1.02	0.07	0.01	0.08	97.8

In the extrusion process, a porthole-type die was employed, which led to the formation of longitudinal seam welds (L-seam welds) along the extruded profile. To investigate the influence of seam welds on the mechanical parameters, the locations of these regions were first identified for both the calibrated and uncalibrated profiles. For this purpose, the profiles were subjected to grinding and etching steps, respectively. The grinding was performed using silicon carbide abrasive papers with 500, 1000, and 2000 grit sizes. The ground profiles were then immersed in a 30% sodium hydroxide (NaOH) solution for 90 seconds. After these steps, the seam welds became clearly visible, allowing more precise extraction of test specimens from the seam weld areas. The profile contained seven longitudinal seam welds with positions as indicated in Fig. 1b.

Characterization of calibrated profiles

Comprehensive mechanical characterization of the effects of the compression calibration process was carried out through uniaxial tensile testing, three-point VDA bending testing, and axial crush testing. First, the mechanical properties of calibrated and non-calibrated profiles were investigated using quasi-static uniaxial tensile testing on an MTS Landmark 50 kN universal tensile testing machine. Tensile tests were performed at room temperature under a constant crosshead speed of 0.085 mm/s. As illustrated in Fig. 2, tensile specimens were extracted from five different positions along the extrusion direction using wire EDM. This approach enabled evaluating the effect of calibration on ductility as assessed by uniaxial tensile testing, considering also the presence of longitudinal seam welds and the sample orientation. Strain was measured throughout the tensile tests using VIC-2D Digital Image Correlation (DIC) system, which enables precise strain measurements.

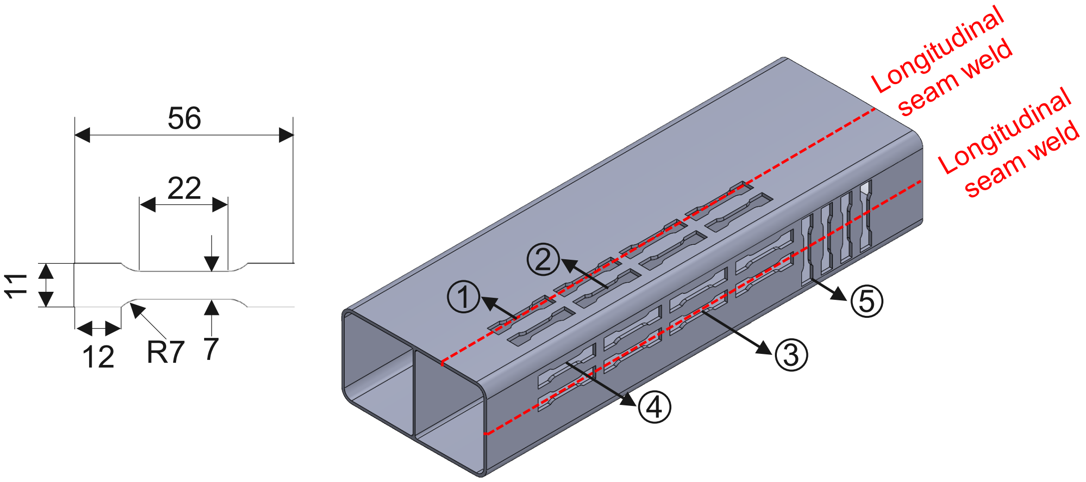


Fig 2. Dimensions and extraction locations of tensile test specimens

Second, the VDA bending tests were carried out using a STEP Lab Axial 20 kN static testing system, where the roller gap was set to 6 mm, the punch radius to 0.4 mm, and the rollers had a diameter of 30 mm. The VDA bending tests were performed under load-drop control, with a constant punch speed of 0.33 mm/s at room temperature. From each profile, four specimens were extracted: two with dimensions of 50 mm × 50 mm and two with 50 mm × 20 mm (see Fig. 3a). The 50 mm × 50 mm specimens were identical in geometry and contained a longitudinal seam weld, but they were oriented differently with respect to the extrusion direction during the VDA bending tests (see Fig. 3b). In the first configuration, the punch line was positioned parallel to the extrusion direction, whereas in the second configuration, the punch line was oriented perpendicular. This configuration was used to evaluate the effect of sample orientation. To evaluate the influence of longitudinal seam welds, two specimens with dimensions of 50 mm × 20 mm were extracted—one containing a seam weld, while the other was taken from a seam-weld free region of the profile (see Fig. 3d). The subsize bending specimens were due to the limited size of the seam weld free areas available in the extruded profiles. During testing, the maximum load was recorded continuously. In addition, the bending angle for assessing the bendability of each specimen was measured manually using a protractor, as illustrated in Fig. 3c. The measured bend angle at fracture was subsequently normalized by the actual initial specimen thickness.

Third, crush tests were performed in the vertical direction at ambient temperature using an Instron 5 MN machine. The top end was cut with a 5° inclination, as shown in Fig. 4, to initiate buckling and thus ensure that the development of the folding pattern started from the upper end of the profile. The crosshead of the testing machine was operated at a constant velocity of 100 mm/min. The test was terminated after the specimens reached a total deformation of 200 mm. During the tests, the force-displacement characteristic was recorded as the primary indicator of crush performance.

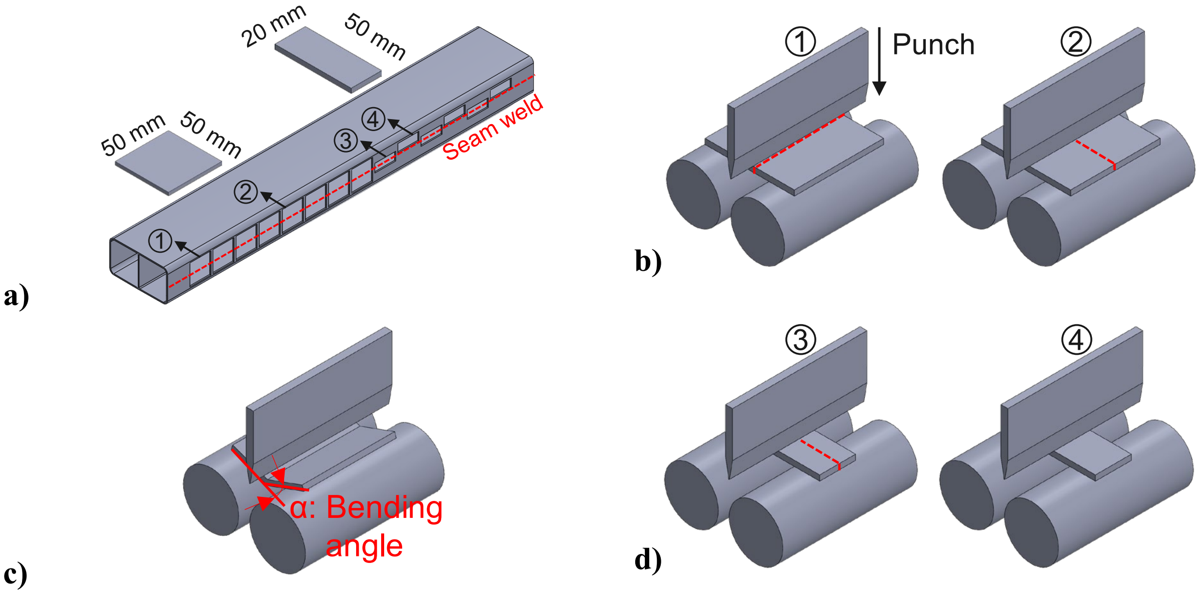


Fig 3. a) Schematic illustration of the test specimen extraction locations **b)** Test configuration of 50 mm x 50 mm specimens **c)** Measured bending angle **d)** Test configuration of 50 mm x 20 mm specimens

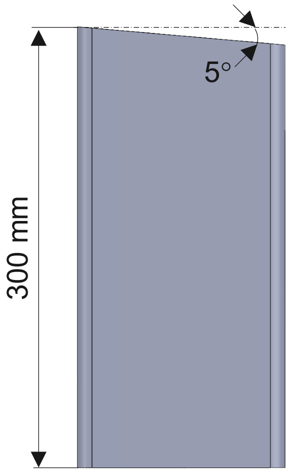


Fig 4. Crush test specimen

Results and Discussion

The investigation begins with the uniaxial tensile test results, which establish the mechanical behavior before and after the compression calibration process. Fig. 5 presents the yield strength, ultimate tensile strength, and logarithmic strain at necking for five different specimens before and after calibration, together with the corresponding standard deviations. Across all tensile specimens, the highest standard deviations were found to be 4 MPa for yield strength and 2.1 MPa for ultimate tensile strength, and 0.01 for the logarithmic strain at the instant of necking. All specimens showed a minor decrease in yield and ultimate tensile strengths after calibration. The overall impact, however, was negligible, since the maximum reduction in yield strength was 2.4%, while the largest decrease in ultimate tensile strength was 3.3%. Compared to the change in strength, a more noticeable reduction was observed in the logarithmic strain after calibration, reaching up to as high as 17.1%. A similar trend was also reported by Qvale et al. [3], who attributed this reduction to a decrease in the work-hardening capacity caused by prior plastic deformation during pre-stretching.

To evaluate the influence of the longitudinal seam welds on tensile properties in the extrusion direction, specimens were extracted from the top (Specimens #1 and #2) and the side (Specimens #3 and #4) walls of the profile. Here specimens #1 and #3 contained longitudinal seam welds. Comparing the results obtained from these specimens revealed that the mechanical properties of the longitudinal seam welds were similar to those of the parent material. In addition, specimens extracted from the same surface but with different orientations (Specimens #3 and #5) were examined. In Specimen #3, the main direction of the tensile sample was parallel to the direction of the seam weld, whereas in Specimen #5, the main direction of the tensile sample was perpendicular to the direction of the seam weld, as shown in Fig. 5. Specimen #5 exhibited lower values of yield strength, ultimate tensile strength, and strain at necking. This observation is consistent with the tensile test results reported by Liu et al. [11].

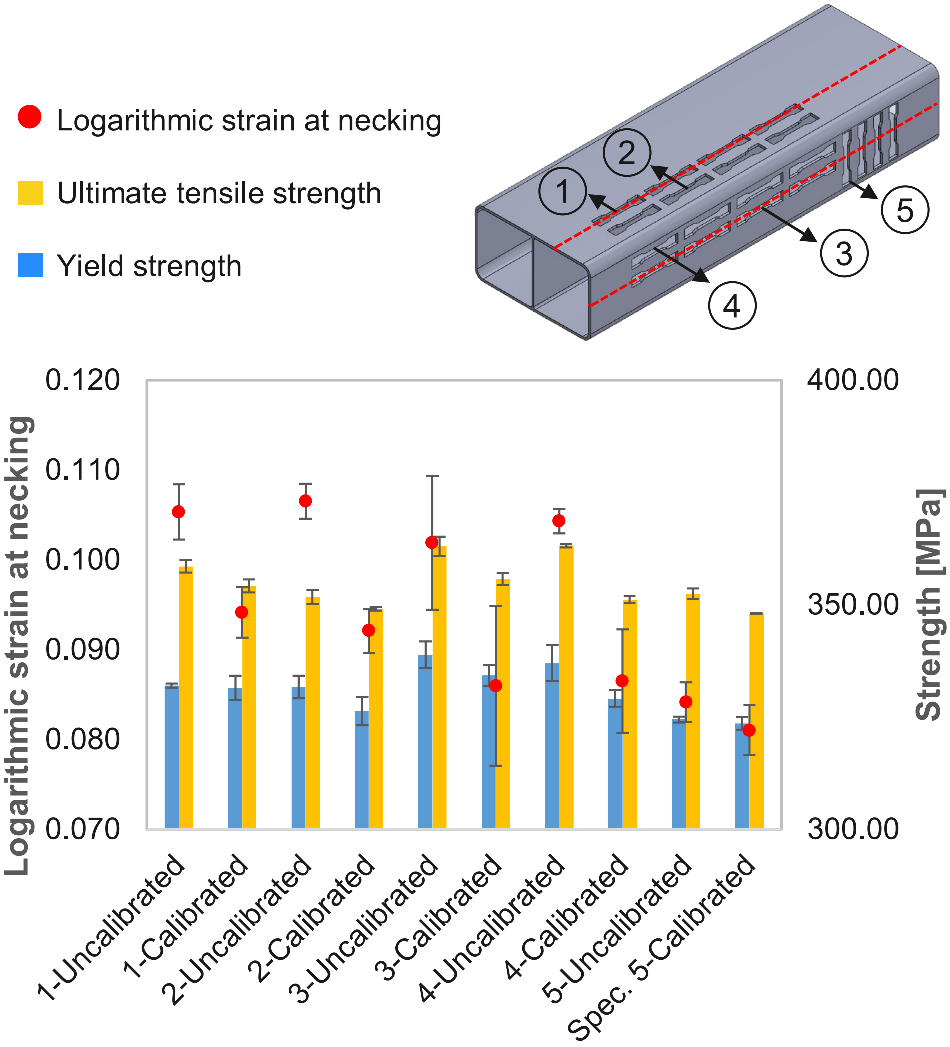


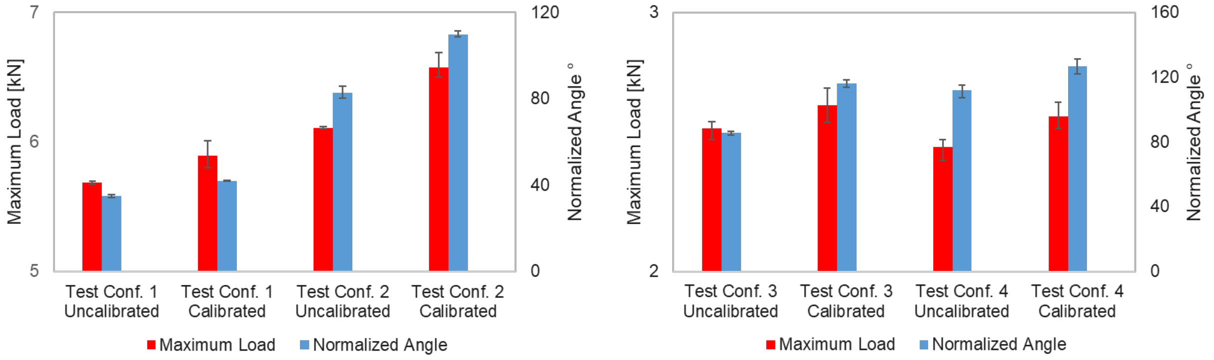
Fig 5. Tensile test results

The effect of the calibration process on bendability was assessed by VDA tests. To examine the effect of the calibration process and sample orientation, two identical 50×50 mm specimens were tested under different loading configurations. Fig. 6a presents the results for Configurations #1 and #2, respectively. In both configurations, the calibrated profiles exhibited higher maximum load and normalized bend angles compared to the uncalibrated ones. In Configuration #1, the normalized bend angle increased by approximately 20.1%, while the maximum load increased by about 3.6% after calibration. In Configuration #2, the enhancements became more evident with the normalized bending angle and maximum load increasing by roughly 32.5% and 7.6%, respectively. This substantial increase in the bend angle clearly indicates that the calibration process enhanced the bendability of the material. Furthermore, when comparing the two configurations, the loading line perpendicular to the extrusion direction (Configuration #2) resulted in significantly higher ductility than loading parallel to it (Configuration #1). This applies to both uncalibrated and calibrated profiles. For the uncalibrated profiles, loading perpendicular to the extrusion direction resulted in approximately

137.6% higher normalized bending angle and 7.4% higher maximum load compared to parallel loading. For the calibrated profiles, the corresponding increases were approximately 162% and 11.6%. These differences indicate that loading parallel to the extrusion direction causes crack initiation to occur earlier, as the perpendicular configuration demonstrated considerably higher ductility.

To investigate the effect of compression calibration on longitudinal seam weld properties, an additional 50 × 20 mm specimens were tested. The specimen in Configuration #3 contained a seam weld, whereas the specimen in Configuration #4 was extracted from a seam-weld free region. Fig. 6b presents the corresponding bending test results. Consistent with the previous findings, the calibrated specimens demonstrated increased maximum load and normalized bend angle in both configurations. In Configuration #3, the normalized bending angle increased by approximately 35.9% and the maximum load by 3.4% after calibration. In Configuration #4, the corresponding increases were around 13.3% and 4.7%. The observed increase in the normalized bend angle indicates that the calibration process does enhance the bending performance and overall ductility. Moreover, the presence of seam welds led to a reduction in normalized bend angles—approximately 23.5% for uncalibrated specimens and 8.3% for calibrated ones, indicating decreased ductility.

Overall, the calibrated profiles had a larger bend angle at fracture in VDA bending tests. This does not align with the logarithmic strain measured in tensile tests. However, it agrees with the results of Zhou et al. [12], who reported a low correlation between the two test methods. They attributed this to fundamentally different fracture mechanisms in tensile and bending type deformations.



a) Test configuration 1 and 2 **b)** Test configuration 3 and 4

Fig 6. VDA bending test results: **a)** Test configuration 1 and 2, **b)** Test configuration 3 and 4

As a final assessment method, axial crush tests were performed to evaluate the global deformation behavior and energy absorption capacity at the component level. Fig. 7a presents the crush test results of the uncalibrated and calibrated profiles. Both the peak force and total energy absorption increased after calibration by approximately 5.4% and 4.5%, respectively. The improvement in the absorbed energy suggests that the calibration process enhanced the performance of the profiles, indicating an increased crushability. Fig. 7b and 7c visually compare the cracks observed to evaluate ductility. The calibrated profiles exhibited shorter and fewer cracks, particularly in the corner regions. This indicates that the calibration process has a positive effect on ductility, as shown by reduced crack formation and a more uniform deformation during axial crushing.

The present findings support the observations made by Parson et al. [8], indicating that yield strength alone is not a reliable predictor of crash performance; although no significant change in yield strength was observed after compression calibration, a significant increase in absorbed energy was recorded in the crush tests. Unlike Parson et al. [8], who reported a linear relationship between ultimate tensile strength and absorbed energy, these results show an increase in absorbed energy, although the ultimate tensile strength remains unaffected by calibration. This indicates that factors other than strength contribute to the observed improvement in crush performance. One potential factor is the dimensional changes introduced by the compression calibration process, which may influence the folding behavior during crushing.

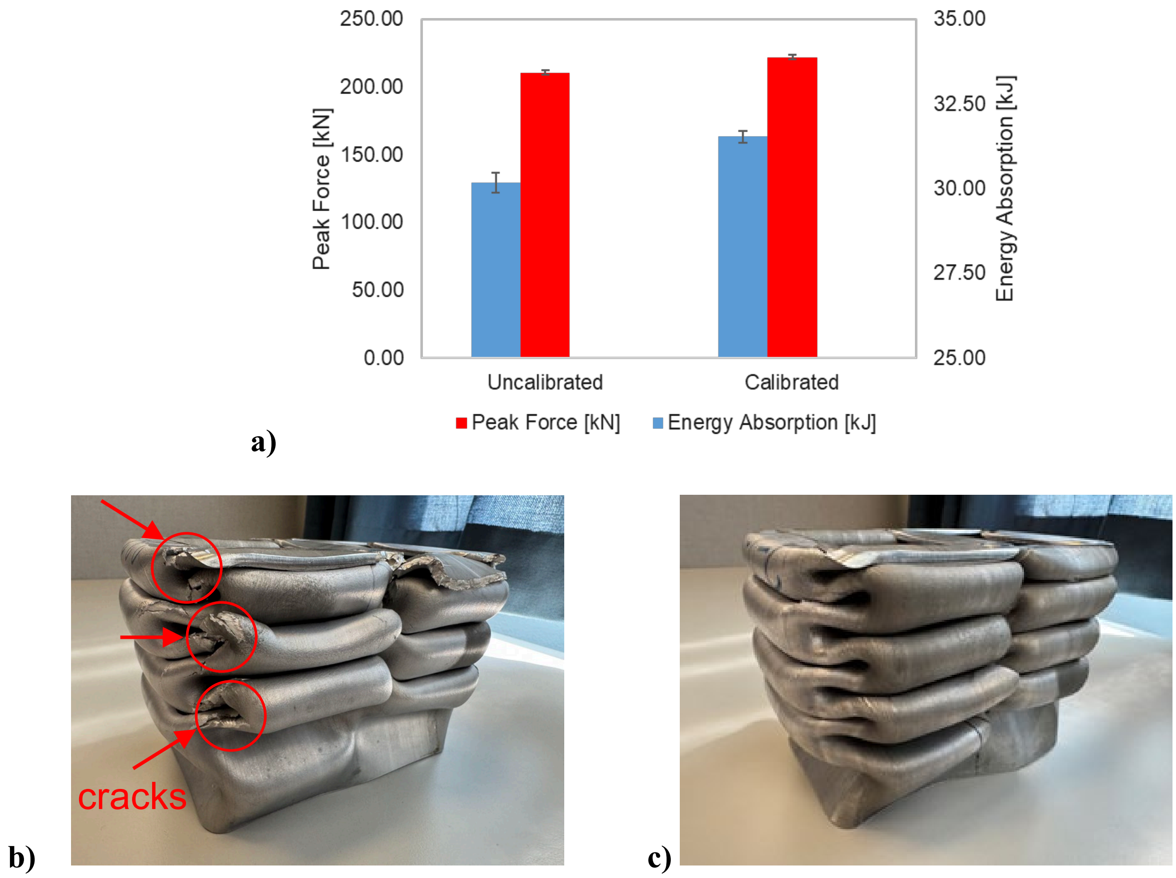


Fig 7. Crush test results: **a)** Peak force and energy absorption results, **b)** Uncalibrated profile **c)** Calibrated profile

Overall, the proposed compression calibration method is a feasible alternative to existing calibration methods in industrial practice. Although the process requires the use of part-specific internal mandrels adapted to the geometry of each individual profile, it can readily be integrated into mass production using conventional presses. In addition to its primary role of improving dimensional accuracy, the present results suggest that the process may also provide added value in terms of improved mechanical performance.

Conclusions and Outlook

This paper introduces a novel compression calibration method designed to improve the dimensional accuracy of complex extruded hollow sections. The aim was to determine the effect of the intermediate calibration stage on the properties of the profiles. This was investigated by examining the mechanical properties of double-chamber AA6061 profiles by uniaxial tensile, VDA bending, and axial crush tests. After calibration, a reduction was observed in the logarithmic necking strain in uniaxial tensile testing. In contrast, the normalized bend angle obtained from the VDA bending tests increased. The crush test results showed that the calibration process enhanced the absorbed energy and reduced the formation of cracks in the profile corner regions. Collectively, although the primary purpose of the compression calibration method is to improve the dimensional accuracy of extruded profiles, the present findings demonstrate that it also contributes to improved mechanical properties. Further research studies will focus on advanced material characterization analyses, such as SEM and EBSD, to investigate in greater depth the underlying mechanisms governing the observed changes in the mechanical response of the calibrated profiles.

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