



THERMAL AND MECHANICAL RESPONSE OF METAL PIPES DURING HOT EXPANSION: AN EXPERIMENTAL AND NUMERICAL STUDY

Ahmed Ibrahim Farhan

Department of Electrical Engineering, College of Engineering/Al-Shirqat, Tikrit University, Salah al-Din, Iraq

ahmed.i.f@tu.edu.iq

[orcid:0009-0001-7782-779X](https://orcid.org/0009-0001-7782-779X)

Abstract. The present work examines how tube-wall thickness and conical die semi-angle govern the thermally assisted expansion response of AA6061 aluminum and BR6040 brass tubing, evaluating two wall gauges (1.5 mm and 2.0 mm) in combination with three die semi-angles (15°, 20°, and 30°). Expansion loads were quantified under both ambient and elevated-temperature conditions to isolate the role of thermal input in governing material response. Across every geometric and material combination examined, forming at elevated temperature was found to substantially lower the peak expansion load relative to the cold condition, with reductions spanning 24–54% depending on alloy, gauge, and die geometry. As a general trend, greater wall thickness raised resistance to plastic flow and consequently demanded higher forming loads, whereas heating to 450 °C for the aluminum alloy and 700 °C for the brass alloy markedly enhanced material formability and lowered flow resistance. Among the two alloys, AA6061 displayed a comparatively steeper load reduction under thermal loading than BR6040, an effect that became more pronounced at larger die angles. These outcomes underscore the capacity of hot expansion to both diminish forming loads and promote greater ductility. In parallel, finite element predictions generated in ABAQUS closely tracked the experimentally measured trends, lending confidence to the numerical model's ability to capture expansion response across the full range of thicknesses and die angles investigated.

Keywords: Hot expansion, End expansion of tubes, Tube flaring, Tube expansion, Finite element.

1. Introduction

Mechanical expansion is a forming operation that exceeds the yield point of the metal or alloy being expanded, causing the expanded material to exhibit a permanent change in shape or dimensions instead of merely an elastic response to the imposed load or state of stress. The induced plastic strain in the workpiece is generally accompanied by a change in its mechanical properties owing to the changes in geometry imposed on the workpiece by the expansion die [1][2].

The mechanical expansion processes of metal tubes encompass practically important operations performed at the ends of the tubes. These include expansion, nosing, flaring, sinking, and flanging. Such operations can be carried out on metals that are highly ductile and formable, that is, they can be shaped without significant changes in the base material properties or failure. However, the deformation must be kept within the limits of formability of the material in order to prevent failure modes such as ductile fracture, local buckling, or wrinkling [3–5].

Tube expansion can be divided into two main categories: steady-state and unsteady-state processes. This work is concerned with the unsteady-state expansion mode, where the deformation is not uniform throughout the process.

Expansion, as illustrated in Figure 1, is widely used in engineering systems where controlled deformation and energy dissipation are of paramount importance. Examples include crash-absorption components for vehicles, pneumatic and hydraulic circuits, exhaust manifolds, fuel-routing grids of engines, heat exchangers, and tube-joining configurations in a variety of mechanical assemblies [6–8].

Ref. [9] studied material instabilities in the expansion of cylindrical tubes using both experimental and numerical methods. The authors identified two main mechanisms limiting the deformation: global symmetric buckling and repetitive necking at the tube ends. They found that buckling tends to decrease the force driving the deformation, which slows the propagation of necking and, consequently, the onset of fracture.

Another study [10] examined the limits of deformation stability in tube expansion using large conical dies with a half-angle of 30° . Using a combined numerical and theoretical approach based on virtual material characterization, the authors concluded that for long tube lengths the limiting failure mode is elastic-plastic buckling, whereas for short tube lengths the failure mode is necking followed by ductile rupture. Ref. [11] investigated, both experimentally and numerically (finite element modelling, FEM), the end expansion of thin-walled pipes. Their findings highlighted that a key consideration when selecting expansion parameters is to remain below the formability limit of the material to prevent ductile fracture, local buckling, or wrinkling. They emphasized two factors for successful deformation: wall thickness and lubrication.

Ref. [12] proposed an analytical model for tube expansion on conical dies, assuming perfect plasticity ($n = 0$); closed-form relationships for stress and strain were derived, and a forming load was estimated. The predicted load–displacement curves showed no definite peak, which the authors attributed to plastic instability (buckling) or localized necking. They also noted that the mechanics of the transitional region between the deformed and undeformed portions of the tube were not fully addressed in their model.

Ref. [13] performed analytical modeling together with experimental testing to investigate end expansion in thin-walled tubes formed with conical dies. Expansion ratio, die semi-angle, and wall-thickness ratio were identified as the governing variables affecting the deformation response. They found that a combination of high expansion ratio and shallow die angle promotes local buckling, while shallow die angle alone increases the risk of ductile fracture.

In a subsequent study [14] on the forming limits of flaring, it was determined that the expansion process proceeded smoothly along the die surface at a fixed semi-angle, with the rupture point occurring at the tube end. It was also reported that when the semi-cone angle was $\alpha = 20^\circ$, the expansion ratio increased with punch stroke, whereas for $\alpha = 30^\circ$ the opposite trend was observed—consistent with the fact that the bottom depth produced by a punch of the same stroke is shallower when the semi-cone angle is larger.

The behavior of microtubes under expansion and flaring at ambient temperature (20°C) was investigated in a previous study [15] and found to be comparable to that of macro-scale tubes. A ductile-fracture criterion was found to be well suited for predicting circumferential fracture locations in these microtubes, and it was observed that both the attainable expansion limit and the circumferential ductility increased with increasing semi-angle and total elongation.

Another study [16] proposed an analytical model for pipe expansion under tension and validated it against finite element analysis conducted in ABAQUS. Very good agreement was obtained between the theoretical and simulated results in terms of tension force and energy dissipated across a range of geometric configurations and friction coefficients; the analysis identified an optimum die-angle window of $22\text{--}25^\circ$, which shifted nonlinearly with increasing friction.

In the present investigation, tube expansion tests were conducted at two different temperatures to examine the effect of temperature on material formability and forming-load behavior. The cold-condition trials were carried out at ambient temperature (around 25°C), corresponding to a state in which the alloys exhibit high strength but relatively low ductility, whereas the hot-condition trials were carried out at 450°C for AA6061 and 700°C for BR6040.

Both processing temperatures lie within the so-called conventional hot-working window—generally considered to be between 0.5 and 0.7 times the absolute melting temperature—where forming techniques become more efficient and load requirements are lower, since ductility is improved, residual stress is partially relieved, and parts are shaped more efficiently [17–20].

This work aims to provide new insight into the hot-end expansion characteristics of AA6061 and BR6040 tubing, considering both wall thickness (1.5 mm and 2.0 mm) and die semi-angle (15°, 20°, 30°) together. The current study combines experimental testing with ABAQUS numerical modelling to demonstrate how increasing temperature not only reduces expansion loads but also increases ductility, whereas previous studies have tended to be either limited in the parameters examined or restricted to cold-forming conditions. The outcome is a dataset that provides useful information for optimizing tube expansion across a range of geometric and thermal conditions.

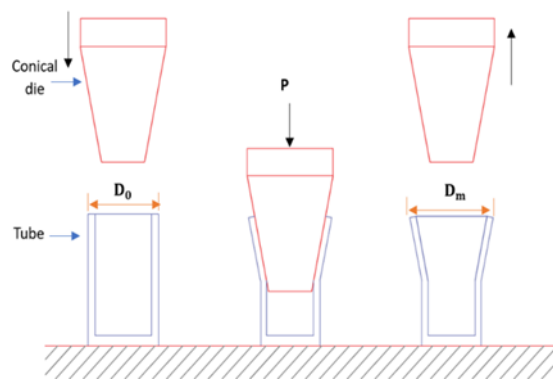


Figure 1. Un-steady state of tube end expansion

2. Numerical analysis

The finite element method (FEM) provides a systematic approach for solving complicated boundary value problems by decomposing them into an assembly of interrelated simple subdomains. Owing to this capability, it is now a standard numerical tool used to obtain a good approximation to the solution in a wide variety of engineering applications. In the present work, the general-purpose finite element program ABAQUS was therefore employed to simulate the pipe expansion process under cold and hot forming conditions [21].

In the numerical model presented in Figure 2, the specimen is a tube and the expansion die is cone-shaped. The geometry of the die and the tube was created, the mechanical properties of the materials were input, and suitable boundary conditions were applied to build the 3D model. The die material was considered rigid and non-deformable, while the tube material was treated as deformable. This material was assumed to exhibit nonlinear plastic behavior, undergo large strain, and behave isotropically [22,23]. It is important to specify the thermal and mechanical properties of the aluminum 6061 and brass 6040 tubes at both room and elevated temperatures in order to accurately simulate the hot-expansion behavior of the tubes. These properties were used as input parameters in the ABAQUS finite element software to achieve a realistic representation of the material response during deformation [24–26].

During the numerical simulation, the tube inner surface and the die were assumed to have a friction coefficient of 0.12. This value was adopted after several comparative evaluations between experimental results and simulation outputs, which showed that a coefficient of 0.12 gave the best agreement in load–displacement behavior for both the cold and hot expansion conditions. The selected value is also consistent with literature-reported friction values for a typical metal-expansion process lubricated with graphite.

A uniform element size of 1.5 mm was used for all tube models in both the cold and hot expansion simulations to maintain mesh consistency and numerical accuracy. This mesh density was established through a mesh convergence study to ensure both computational

efficiency and result accuracy. The mesh was refined sufficiently to resolve deformation gradients near the die-contact and expansion regions while maintaining stable simulation performance.

The two numerical inputs (interfacial friction coefficient and element size) were held constant across all thickness and thermal cases studied to keep the simulation set internally comparable and to eliminate the influence of the other variables under study (geometric and thermal).

The punch velocity in the ABAQUS simulations was fixed at 1 mm/min, matching the physical trials, to maintain equivalence between the two. This common loading rate enabled direct and meaningful comparison of load–displacement responses and strain evolution under equivalent quasi-static loading conditions.

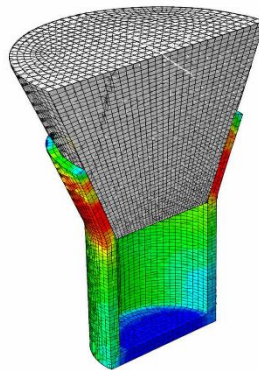


Figure 2. FE model for tube end expansion

3. Experimental Part

The aim of the experimental work was to understand the hot and cold expansion behaviour of AA6061 aluminium and BR6040 brass tubes of varying thicknesses under the similar die-geometry conditions. The inner diameter of all the tested tubes remained constant (28 mm) but the wall thickness varied (1.5 mm, 1.8 mm, 2.0 mm and 2.6 mm). Expansion has been carried out by means of a conical die for the fixed semi-cone angle of 15°.

Both the expansion and tensile samples of AA6061 aluminum and BR6040 brass were heat-treated to relieve residual stresses and increase ductility prior to expansion and tensile testing. The aluminum samples were annealed at 350 °C, while the brass samples were annealed at 550 °C, with each alloy held at the desired temperature for one hour. All specimens were then furnace-cooled slowly to ensure uniform softening of the microstructure and consistent mechanical properties. This heat treatment was necessary to prepare the initial material state prior to the cold and hot expansion tests. Expansion was carried out under two thermal conditions: cold expansion (room temperature, 25 °C) and hot expansion (elevated temperature, 450 °C for aluminum and 700 °C for brass).

The tube expansion tests were performed using a high-capacity microcomputer-controlled electronic universal testing machine, which allows precise control of displacement and load during expansion operations. A constant punch speed of 1 mm/min was maintained for all expansion experiments, such that the loading condition could be considered quasi-static, with the same deformation behavior across all test cases. The equipment was configured so that axial displacement was applied via a conical die inserted into the tube, while reaction forces were measured to obtain accurate load–displacement curves for each material and configuration. To characterize the mechanical behavior of the materials, uniaxial tensile tests were performed on both aluminum and brass under cold and hot conditions. Figure 3 shows the tensile test setup for Al and brass under cold expansion conditions. The stress–strain curves for aluminum at various temperatures are shown in Figure 4, and the corresponding curves for brass are shown in Figure 5. The size and shape of the tubular samples used in the experiments are shown in Figure 6, and Table 1 lists the sample dimensions (1.5 and 2 mm thickness).

Following the tensile tests, tube expansion tests were conducted. During expansion, the inner surface of the tubes was lubricated with graphite, and the same lubricant was applied to the outer surface of the conical dies to reduce friction between the tube and die.

The strain-hardening behavior of the two alloys was characterized by fitting the recorded true stress–true strain curves with the simplified Ludwik relation, obtained by taking the natural logarithms of the true stress and true strain values in the plastic region of the curve where strain hardening occurs, as given below in the form of a constitutive equation [27,28]:

$$\sigma = 192\epsilon^{0.142} \quad \text{for AA6061}$$

$$\sigma = 940.5\epsilon^{0.5881} \quad \text{for BR6040}$$

The Ludwik-type constitutive equations derived from the true stress–true strain relationships of both alloys clearly reveal the distinct differences in their response under cold-forming conditions, and serve as an important input for accurately predicting expansion behavior in subsequent modelling and simulation. The differing strain-hardening behaviors, reflected in the Ludwik parameters, highlight the mechanical differences between the alloys under cold deformation. Thermal softening and high atomic mobility cause both strength coefficient (K) and strain-hardening exponent (n) to drop significantly for expansion at hot temperatures. The reduction results in better formability, lower flow stress, and smoother response of the material to deformation. Hot expansion consequently is advantageous to enhance ductility and to form complicated shapes with lower force applied without fracture [29–31].

The geometry, dimensions and surface condition of the tubular specimens used for the expansion tests after heat treatment are displayed (Figure 7). Each sample was fabricated to a standard length as necessary for the tensile and expansion tests

Moreover, the figure 8 presents the conical dies that are employed in the cold and hot expansion method. Three die semiangles (15°, 20° and 30°) were designed to investigate the influence of die geometry on the expansion behavior. All of the die were carefully machine worked with a smooth outer surface and with proper dimensions for correct alignment with the tube specimens. The cone angle is an important parameter of the experimental setup and of the numerical simulation because the shape of the deformation path, as well as the stress pattern during expansion, depends directly on the cone angle.

Rapid and uniform heating of the metallic tube to the desired temperature (450 °C for aluminum, 700 °C for brass) was achieved in the hot-expansion stage by application of an induction heating system. Induction heating has certain unique benefits for hot metal expansion; it allows for localized heating, accurate temperature control and is an effective way to reduce oxidation. The system operates on the principle of electromagnetic induction, in which a coil of copper wire carries an alternating current to generate a rapidly changing magnetic field. Eddy currents are induced within a conductive material (such as aluminum or brass) placed in this field, generating internal heat through the material's electrical resistance. In this way, the tube walls are heated efficiently and in a controlled manner, yielding thermal homogeneity and minimizing temperature gradients prior to expansion. A non-contact infrared thermometer was used during heating to ensure that the correct temperature was reached and maintained before expansion. The induction heating device used in the experiments is shown in Figure 9, along with the position of the coil relative to the specimen and the heating arrangement applied before the expansion stage.

Table 1. Dimensions of the samples for each thickness.

t_c	r_i	r_0	r_m
1.5mm	14 mm	15.5 mm	14.75 mm
2 mm	14 mm	16 mm	15 mm

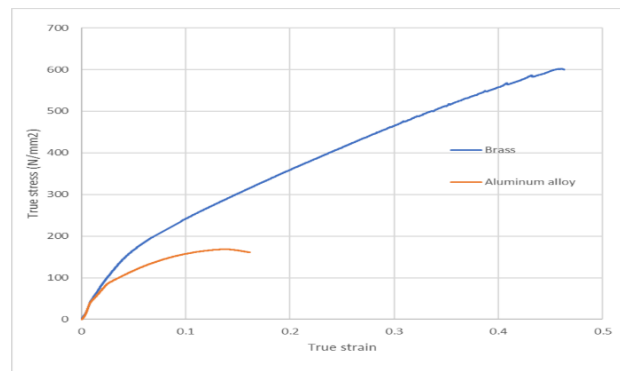


Figure 3. True stress and True strain curve for AA6061 and BR6040 alloy

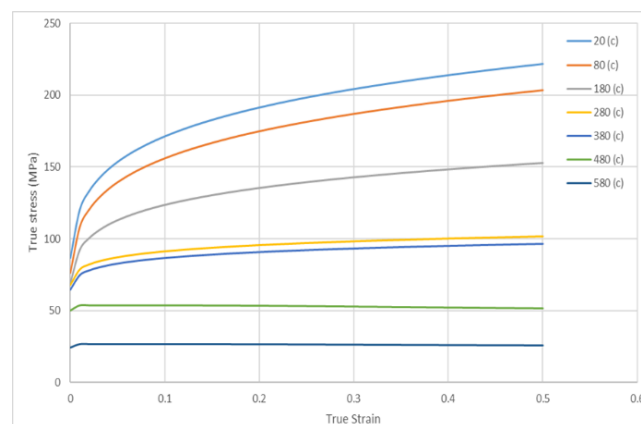


Figure 4. True Stress-True Strain at different Temperature for AA6061.

Table 2 shows the important physical and mechanical properties of aluminum 6061 at 25 °C and 450 °C, including Young's modulus, Poisson's ratio, density, thermal conductivity, specific heat capacity, and yield strength. The values were selected with reference to experimental data to reflect the real behavior of the material under hot expansion conditions.

Table 3 lists the corresponding properties of brass 6040 at 25 °C and 700 °C. These properties are likewise essential to the ABAQUS simulations and central to capturing the thermal–mechanical coupling of the material during the expansion process [32–35].

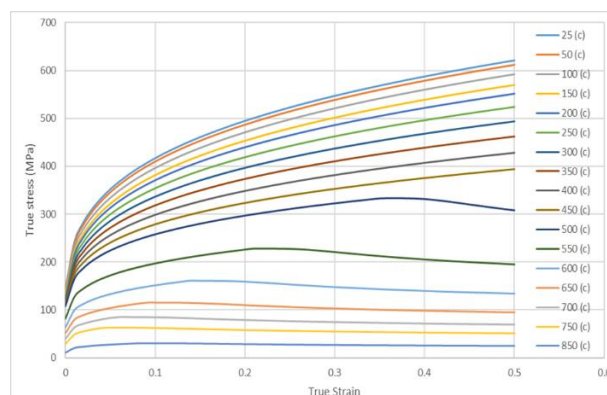


Figure 5. True Stress-True Strain at High Temperature for BR6040.

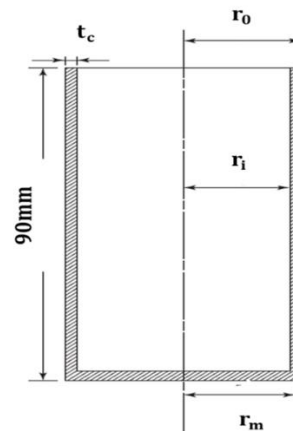


Figure 6. General geometric shape of thickness.



Figure 7. Manufactured expansion samples.



Figure 8. Three conical dies used in study.

JL-15KW Induction Heating Machine



Figure 9. The induction heating machine.

Table 2. Properties for aluminum alloy (6061) at cold and hot expansion.

Properties	AA6061 (25°C)	AA6061 (450°C)
Young Modulus (E)	68.42 GPa	50.58 GPa
Yield stresses	86.55 MPa	49.8996 MPa
Thermal Conductivity	224 W/m. k	215 MPa
Specific Heat	0.9004 J/g. k	1.0916 J/g.k
Poisson ratio	0.3386	0.3616
Density	2.715 g/cm ³	2.624 g/cm ³

Table 3. Properties for Brass alloy (6040) at cold and hot expansion.

Properties	BR6040 (25°C)	BR6040 (450°C)
Young Modulus (E)	100 GPa	60 GPa
Yield stresses	144.3016 MPa	39.7932 MPa
Thermal Conductivity	132 W/m.k	130 MPa
Specific Heat	0.461 J/g.k	0.59 J/g.k
Poisson ratio	0.33	0.34
Density	8.201 g/cm ³	8.104 g/cm ³

4. Results and discussion

The thickness of the wall also has a significant effect on the resistance to plastic flow and, hence, the force required to force the tube through complete expansion at ambient and elevated temperatures for both alloys. It is depicted in Figure 10 which shows the measured load–displacement responses of the 1.5 mm and 2.0 mm aluminium tubes subjected to the 15° die under both cold and hot conditions. The data show that as the wall thickness increases so too does the peak load, that the displacement at failure varies slightly for each wall thickness, and that there are two types of failure: abrupt and more gradual collapse.

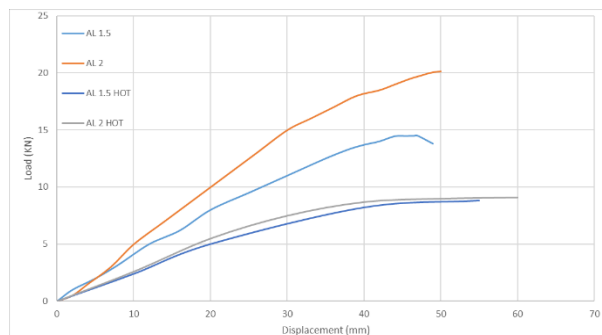


Figure 10. Experimental Load-Displacement of AA6061 at angle (15°).

The responses at elevated temperature lie below the responses at room temperature in the plot. All traces have an initial upward trend, because the greater the amount of die pushed into the bore of the tube, the more stress in the tube, and the more stress, the more force that must be applied to continue pushing the die, which is a strain hardening process before failure. The maximum load recorded was the thicker specimen tested at cold (about 20.15 kN) while the corresponding specimen tested at hot only recorded about 9.1 kN. Beyond this maximum all curves bend downward, indicating the presence of microcracks or loss of local

stability, until the tube reaches eventual failure. The steep falls associated with the cold-formed curves suggest that the material has reached the limit of its stress carrying capacity, which becomes greater as the material is made thicker due to the associated increase in hardening and the more brittle nature of fracture under such conditions. The hot-formed curves, on the other hand, fail at much lower levels as the increased temperature increases the ductility of the material and reduces its mechanical resistance, thus delaying the build-up of stresses in the area and the formation of cracks. The load reduction under this die angle (15°) for the aluminium alloy from cold to hot state is reported in Table 4.

Table 4. Reduction factor between cold and hot expansion (15°).

Thickness (mm)	Max load-cold expansion (KN)	Max load-hot expansion (KN)	Reduction factor (%)
1.5	14.68	8.8	40%
2	20.15	9.1	54.8%

These values suggest that the load-reducing effect of hot expansion grows with increasing wall thickness, indicating that thermal softening is most effective in thicker-walled sections.

The load–displacement traces for the experimental tests conducted with a 20° half-angle die are shown in Figure 11, for 1.5 and 2.0 mm thick AA6061 tubes under both thermal regimes. In each case, the curves originate from zero load and displacement, then increase steadily to a maximum before decreasing—more or less gradually, depending on the forming conditions.

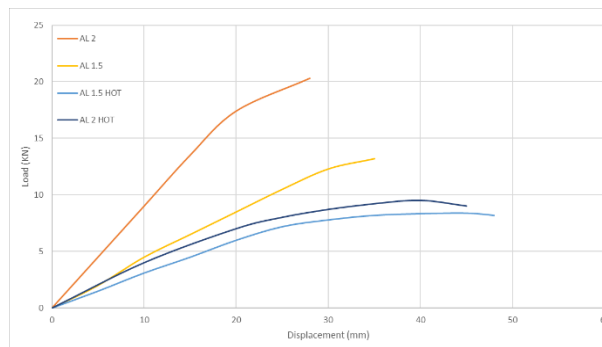


Figure 11. Experimental Load- Displacement of AA6061 at angle (20°).

As shown in Figure 11, the cold-expansion curves consistently occupy the upper part of the load–displacement plot, whereas the hot-expansion curves lie in the lower part—a reflection of the substantial load reduction provided by hot expansion. A common finding is that greater wall thickness corresponds to higher load, regardless of thermal state, indicating that resistance to deformation is directly proportional to section thickness. The initial portion of each curve is an ascending segment corresponding to the strain-hardening phase, in which load increases as the tube elongates and its inner surface offers increasing resistance to the moving conical die. Almost all traces fall below the load maximum as a result of the initiation of microcracks or local failure of the structure, especially at low temperatures where the material is not very ductile and fails suddenly. In contrast, the hot expansion response is much more ductile, meaning the load rises at a lower rate, the peak is lower compared with the cold load condition, and several of the curves don't fracture but are rather more stable or slope off slightly. This is because the tube is thermally softened and thus is able to withstand load over a larger displacement range without failure due to a more even internal stress distribution. The load-reduction factors corresponding to the same angles between the cold and hot conditions are shown in Table 5 for the aluminum alloy.

Table 5. Reduction factor between cold and hot expansion (20°).

Thickness (mm)	Max load-cold expansion (KN)	Max load-hot expansion (KN)	Reduction factor (%)
1.5	13.2	8.4	36%
2	20.42	9.5	53%

The results indicate that the largest load reduction occurs at the 2.0 mm gauge, reflecting a favorable thermal balance, with reduced load and increased formability without compromising structural integrity.

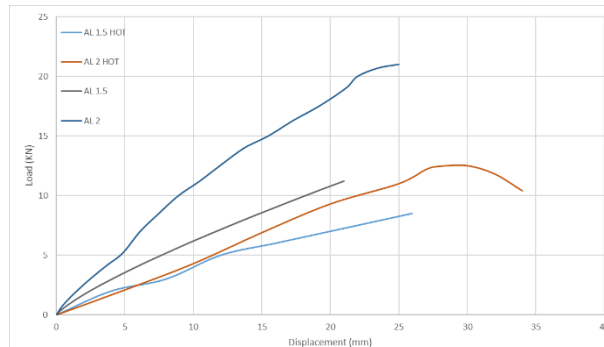


Figure 12. Experimental Load- Displacement of AA6061 at angle (30°)

Figure 12 shows the experimental load–displacement behavior for pipe expansion with the 30° half-angle die, for the tested thicknesses under both thermal conditions. The systematic variation of the curves with thickness and temperature reflects the direct influence of these two parameters on mechanical performance during forming. In general, the material response occurs in two stages: an initial stage in which the load increases with displacement, and a second stage in which it decreases or remains relatively constant after reaching a peak—a sign of incipient failure and/or progressive yielding. The corresponding cold-to-hot load-reduction factors for this 30° die angle for the aluminum alloy are shown in Table 6:

Table 6. Reduction factor between cold and hot expansion (30°).

Thickness (mm)	Max load-cold expansion (KN)	Max load-hot expansion (KN)	Reduction factor (%)
1.5	11.2	8.5	24%
2	21	12.5	40%

Having shown that the aluminum alloy responds differently depending on thickness and die angle, the focus now shifts to brass formed under the same conditions, allowing comparison of the two materials' forming characteristics in terms of mechanical properties and underlying metallurgical structure. This comparison serves to clarify the effects of thickness and die angle on brass and to identify similarities and differences between the two materials in terms of load magnitude, formability, and thermal sensitivity. All experimental load–displacement curves shown in Figure 13 exhibit a monotonic increase in load with displacement, followed by a sharp or gradual decrease depending on the forming regime, for brass at a 15° die angle in both thicknesses (1.5 and 2 mm) under cold and hot conditions.

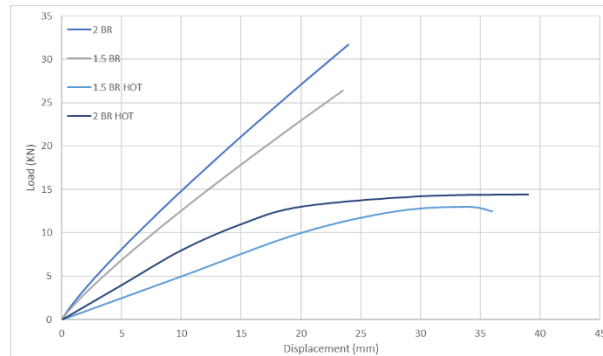


Figure 13. Experimental Load- Displacement of BR6040 at angle (15°).

The hot-expansion traces had a notably smoother shape, indicating that lower loads were required and greater displacement could be achieved before failure, compared with brass under cold-forming conditions, which exhibited a sharp rise to a peak load followed by an abrupt break at the end of the curve. Greater wall thickness corresponded to higher achievable load under both thermal conditions, which is expected, since increasing wall thickness provides greater resistance to deformation due to increased hardness and cross-sectional area at larger gauges. This load-reducing effect of increased temperature was found to be consistent across all thicknesses and was attributed to increased intergranular sliding resulting from softening of the brass matrix at higher temperatures, which lowers the load required to achieve a given displacement. Under cold conditions, brass was found to be substantially more load-bearing than aluminum, particularly at the larger gauge, where brass reached a maximum load of 30 kN at 2 mm compared with 21.15 kN for aluminum, reflecting the relatively harder state of brass when unheated.

However, under hot-forming conditions, the load difference between the two thicknesses decreased markedly, indicating that thermal softening partially compensates for the effect of section thickness; the post-peak drop was also smoother rather than abrupt, indicating improved ductility and extended tolerance for further deformation. The load-reduction factors for brass at a 15° die angle, from cold to hot conditions, are shown in Table 7.

Table 7. Reduction factor between cold and hot expansion (15°).

Thickness (mm)	Max load- cold expansion (KN)	Max load- hot expansion (KN)	Reduction factor (%)
1.5	26.38	13	50%
2	31.7	14.4	54%

Thermal expansion appears more beneficial to brass than to aluminum relative to their cold-state hardness, with the load reduction from heating being greater for brass. The results at 15° overall indicate that brass is sensitive to both thickness and temperature, the former governing strength and the latter determining the extent of load reduction.

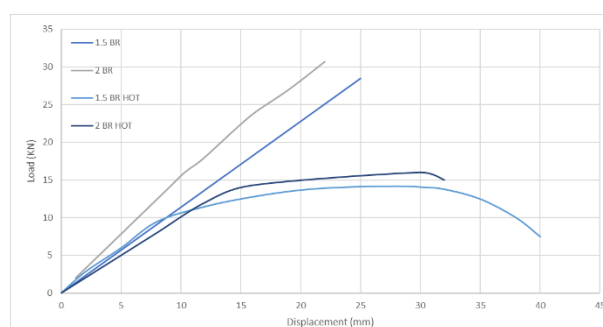


Figure 14. Experimental Load- Displacement of BR6040 at angle (20°).

The load–displacement curves for the 20° brass dies at both thicknesses (2 and 1.5 mm), under cold and hot conditions, are shown in Figure 14. The load increases gradually with displacement, reaching a maximum before decreasing—either abruptly or smoothly, depending on thermal state—though the response differs owing to the different die-contact geometry. The load-reduction factors for brass at this 20° die angle are shown in Table 8.

Table 8. Reduction factor between cold and hot expansion (20°).

Thickness (mm)	Max load-cold expansion (KN)	Max load-hot expansion (KN)	Reduction factor (%)
1.5	28.4	14.2	50%
2	30.7	16	47%

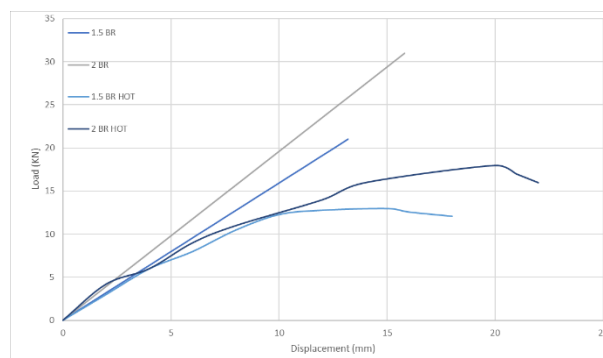


Figure 15. Experimental Load- Displacement of BR6040 at angle (30°).

The brass load–displacement curve for the same range of thicknesses is plotted in Fig. 15 for both thermal conditions at a 30° die angle. All curves increase monotonically with displacement up to the ultimate load, which then drops sharply at fracture, with the 2 mm specimen achieving the highest ultimate load of 31 kN. The curves also originate from zero load but rise much more slowly and reach a lower maximum load than the cold-condition curves—the 2 mm hot-formed specimen peaks at 18 kN, for example, about 13 kN lower than the cold-formed specimen. The corresponding cold/hot load-reduction factors for brass at this 30° die angle are given in Table 9.

Table 9. Reduction factor between cold and hot expansion (30°).

Thickness (mm)	Max load-cold expansion (KN)	Max load-hot expansion (KN)	Reduction factor (%)
1.5	21	13	38%
2	31	18	42%

The reduction factors ranged from 38% to 44%, showing that nearly half the load was reduced through hot forming—a notable industrial advantage in terms of energy savings and increased tool life. The benefit was greatest at the 2 mm gauge, indicating that this thickness is most sensitive to thermal effects among the materials studied.

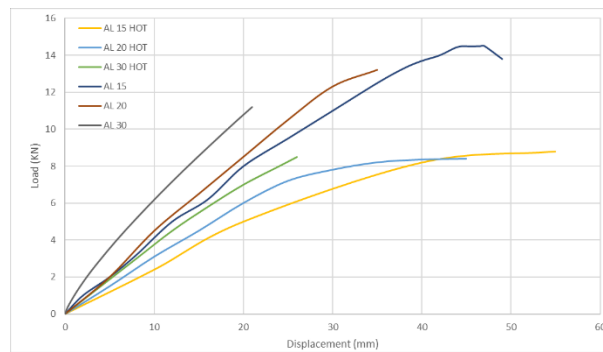


Figure 16. Experimental Load- Displacement of AA6061 at thickness 1.5mm.

The load–displacement responses of the 1.5 mm aluminum tube are shown in Figure 16 for the three die semi-angles (15°, 20°, and 30°) under cold and hot forming. Under cold conditions, load accumulates gradually with displacement up to several sharp post-peak declines, indicating sudden failure. The hot-condition curves, by contrast, are all notably smoother, steadier, and lower, reaching lower peak loads at the same angles and declining more gradually than the cold-condition curves. In all cases, the initial rise in load reflects the inherent resistance of the metal to plastic deformation; this rise is greater under cold conditions due to strain hardening, whereas the ductile nature of the heated metal produces lower load for the same plastic displacement, and the smooth curves without a sudden post-peak drop under hot conditions indicate that strain hardening and early failure are less pronounced than under cold conditions. Under cold conditions, the load required for a given displacement increased with increasing die semi-angle; this was attributable less to the angle itself than to the more abrupt deformation mode imposed by the steeper die face, which increases resistance to expansion as strain concentrates over a shorter effective contact length, but which can also lead to excessive friction or a more non-uniform deformation mode.

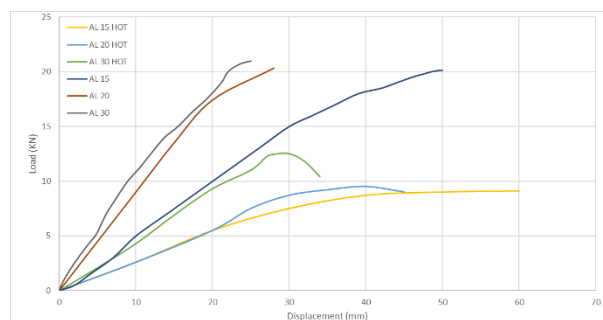


Figure 17. Experimental Load- Displacement of AA6061 at thickness 2mm.

The corresponding load–displacement responses for the 2 mm aluminum tube at three die angles, under cold and 450 °C hot-forming conditions, are shown in Figure 17. The cold-condition curves show a steady increase in load with displacement up to a distinct peak, representing the maximum load the tube can withstand before failure. Interestingly, die angle increased load only during the first stage of deformation—due to the greater resistance created by the sharper geometry of the higher die angle—but the earlier failure of samples at these higher die angles, driven by higher stress, resulted in decreased peak load and formability, consistent with increased friction at the die–tube interface, which creates greater resistance to deformation.

The same experimental approach was applied to brass; having characterized the effect of die semi-angle on the aluminum alloy, the same procedure was carried out for brass to characterize its behavior and identify any differences relative to aluminum. The load–displacement response of 1.5 mm brass tubes for the 15°, 20°, and 30° die angles is illustrated in Figure 18, for cold and hot (700 °C) forming. The cold-condition curves tend to end in sudden post-peak failure, suggesting a relatively brittle failure mode once the material reaches

the end of its plastic limit. In addition, load levels at 700 °C were substantially lower than under cold forming at all angles, with a smoother curve, indicating more ductile behavior and greater deformability under hot forming. This behavior is thermally activated and associated with several interacting microscale mechanisms, particularly a significant drop in the yield strength of brass, which under these conditions undergoes extensive dislocation slip, together with dynamic recrystallization, which continuously generates new fine grains, softening the material and facilitating deformation without requiring high load. Brass, on the other hand, exhibited a more stable cold curve than aluminum and was found to be stronger overall at the common test gauge of 1.5 mm; however, once the peak load was exceeded, brass proved more brittle than aluminum, with a more abrupt drop in load after yielding, and its yield stress was found to decrease with increasing temperature, unlike aluminum's.

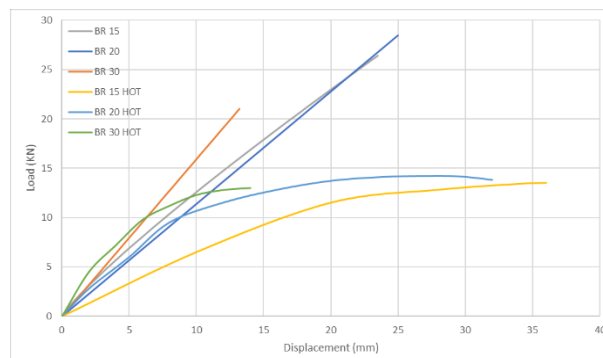


Figure 18. Experimental Load- Displacement of BR6040 at thickness (1.5 mm).

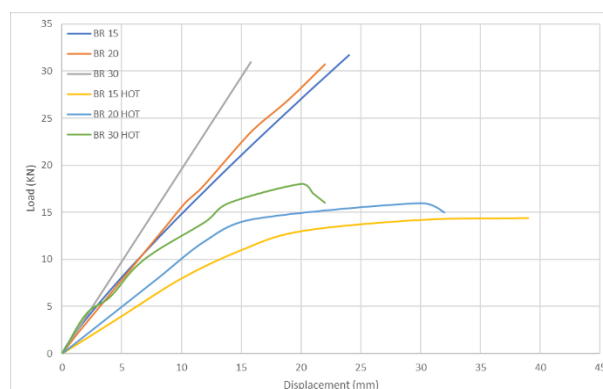


Figure 19. Experimental Load- Displacement of BR6040 at thickness (2 mm).

The results obtained for three different semi-die angles (15°, 20° and 30°) for both hot and cold forming of the brass specimens of thickness 2 mm are presented in Figure 19. The load–displacement curves show different mechanical behavior at different angles as the combined effect of die geometry and temperature, and the peak load and total displacement both change from angle to angle, indicating that die angle is an important parameter to affect the load–displacement response.

For cold forming, the load was higher as the die angle became steeper because of the higher flow resistance of the steeper angle die geometry and the higher compressive stress needed to make up for the combined effect of friction and resistance to deformation. This increased angle also restricted the overall displacement, as the metal was less able to expand than with shallower angles. The 15° and 20° orientations, however, resulted in less severe load response, suggesting a less severe and gradual deformation path compared to the 30° orientation. The situation under hot-forming conditions was quite different: all curves showed a lower peak load than did the corresponding cold-condition curve, and this lower peak load was not only due to the effect of reduced strength of brass with temperature, and the corresponding decrease in

yield stress with temperature, but also due to some dynamic-softening effects.

For complement to the experimental analysis and to validate the results, the mechanical behavior under different expansion conditions was simulated using ABAQUS. Numerical models were developed using material properties measured at room and elevated temperature, appropriate boundary conditions and friction coefficients. The simulation results contributed to the understanding of the deformation pattern, the load response, and the sensitivity to the geometric parameters (wall thickness, die angle etc.). In the next section, a comparison of the experimental and numerical results is made, highlighting their agreement as well as some key discrepancies.

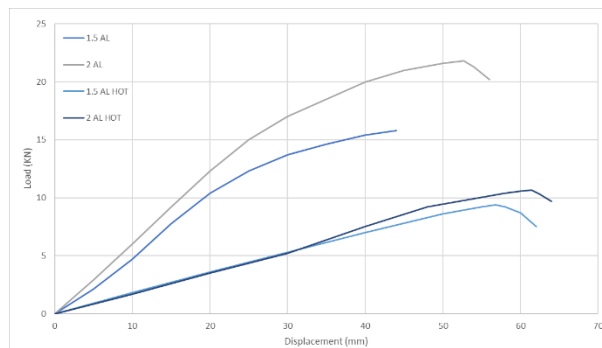


Figure 20. Theoretical Load-Displacement of AA6061 at angle (15°).

The largest deviations between measured and calculated expansion loads occurred across all simulated cases at a die semi-angle of 15°, for both wall thicknesses (1.5 mm and 2 mm) under cold and hot expansion conditions. The hot-expansion case showed the highest percentage error at 2 mm thickness (14.7%), while the cold-expansion cases showed lower percentage errors of 8.0% at 1.5 mm and 7.5% at 2 mm. The error for hot expansion at 1.5 mm was 6.3%.

These results indicate that the numerical load values were consistently higher than the experimental ones, which may be attributed to the assumption of a perfectly isotropic and homogeneous material, idealized friction and boundary conditions, and the absence of microstructural imperfections and/or softening phenomena observed in the material during the deformation experiments.

Despite these differences between the numerical and experimental results, the overall agreement is good, supporting the validity of the numerical model. The consistent trend of the curves across different thicknesses and expansion conditions further confirms the model's predictive power.

5. CONCLUSIONS

1. Hot expansion reduced the peak expansion load by 24% to 54%, depending on thickness, angle, and material.
2. AA6061 aluminum exhibited a more pronounced reduction in load under hot conditions than BR6040 brass.
3. Increasing die angle led to higher expansion resistance across all tests.
4. Thinner tubes (1.5 mm) were more affected by expansion temperature and die geometry.
5. Hot expansion improved ductility and lowered the risk of fracture compared to cold expansion.
6. The comparison between numerical and experimental results showed generally good agreement in terms of load trends and deformation behavior when coefficient of friction ($\mu = 0.12$) were used. However, the maximum deviation in peak expansion load was observed in the hot expansion case with 2.0 mm thickness and 15° die angle, where the numerical model overestimated the load by 14.7%. This variation highlights the sensitivity of numerical predictions to material modeling and boundary assumptions, yet confirms the reliability of the simulation approach for capturing overall expansion

behavior under varying thermal and geometric conditions.

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